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Vacuum Tubes in the Physics Laboratory

G. P. HARNWELL AND L. N. RIDENOUR

Randal Morgan Laboratory of Physics, University of Pennsylvania, Philadelphia, Pennsylvania

THE vacuum tube and small gas discharge tube are two of the most flexible instruments at the disposal of the physicist. They were developed in physical laboratories and, though their more recent adaptations and refinements are largely due to the communication industries, they are continually finding new uses in physical research and instruction. We are further indebted to their commercial application for the ready availability of all the indispensable circuit elements, such as resistances and condensers, that are associated with them. From time to time complete treatises appear dealing with both communication and laboratory applications but the periodical literature is so voluminous that occasionally it is worth while to make a survey of the circuits of particular interest to physicists. Since it is not possible in an article of this length to refer to all the circuits that have been proposed within the past few years, only representative applications which the authors have found to be of the greatest service or most widely used are presented. In a few instances, such as the constant-current nets, circuits that have long been known but have not found as wide application as they warrant are briefly recalled. Most of the descriptions, however, are of quite modern developments or of improved technics adapting modern equipment to older types of circuits resulting in more convenient or more flexible tools for the research or instructional laboratory.

1. RECTIFIERS

One of the commonest laboratory applications of electron tubes is their use as rectifiers in power supplies designed to give direct current from the alternating-current lines. The laboratory functions most often performed by such electron tube rectifiers are (*a*) supplying direct current for other electron tube circuits, (*b*) providing constant potential for ionization chambers, multiplication counters (Section 5) and other apparatus, (*c*) serving as d.c. power supply for x-ray tubes, electron diffraction cameras, positive ion tubes and other high voltage equipment. The output of such a rectifier is pulsating, and this ordinarily necessitates the insertion beyond the rectifier of a filter circuit, whose function is to smooth the ripple in the rectifier output. The principles and design of the most commonly employed rectifier and filter circuits are adequately treated in standard textbooks,[1] and we shall restrict ourselves here to a description of some less well-known power supply circuits which are suited to special purposes.

The transformerless doubler

A useful rectifier which is capable, at light loads, of supplying direct-current voltages about twice the a.c. line voltage without the use of a transformer is shown in Fig. 1. On alternate halves of the a.c. cycle, the two condensers which

[1] Reich, *Theory and application of electron tubes* (McGraw-Hill, 1939), chap. XIV.

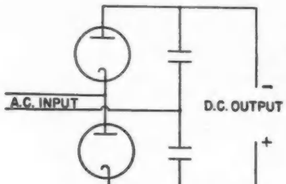


FIG. 1. Voltage doubling circuit.

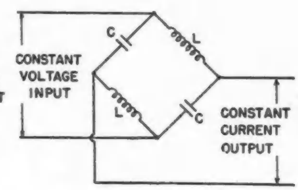


FIG. 2. Monocyclic square.

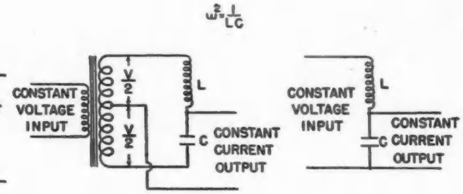


FIG. 3. Constant-current circuits.

are connected in series are charged through the two rectifier tubes shown. Separate filament supplies for the two rectifiers must be provided, unless one uses a rectifier tube with two cathodes insulated from each other but having a common heater. Such tubes are the 25Z5 and 25Z6. This circuit is eminently well suited for electroscope charging and similar low current applications. It should be noted that the 25-v heater of the 25Z5 may be supplied from a 115-v line with a 30-w, 300-ohm resistor in series, thus avoiding altogether the use of transformers. Somewhat more complicated circuits will provide four or more times the input line voltage.[2]

Constant-current rectifier

It is sometimes desired to supply a constant direct current for the operation of arcs or other devices with current-voltage characteristics of negative slope which tend to instability. The primary of a phanotron rectifier may be supplied with alternating current from a constant-current a.c. network, one form of which, the monocyclic square, is shown in Fig. 2. If the product LC is adjusted so that the impedances of the condensers are equal, at the line frequency, to those of the inductances, the output current of such a circuit is independent of the resistance of its load to the approximation that the resistance of the windings of the inductance may be neglected. Also neglected has been the fact that the value of an iron-core inductance is a function of current, so that the condition of resonance is strictly fulfilled only for one value of load. If the inductances be made with large air gaps, however, the latter effect may be kept small. Simpler alternative constant-current circuits are shown in Fig. 3. Such a device is coming into favor to control the plate power supply for the high power radiofrequency oscillator used to excite the dees of a cyclotron. Bursts of gas in the accelerating chamber, which would cause the striking of an arc between the dees with the possibility of destructively large currents in the conventional arrangement, are completely harmless to an outfit protected by a constant-current plate power supply; for, in distinction to the ordinary constant potential power sources, these may be short-circuited with impunity. They can be protected against the damage that would be caused in open-circuiting the terminals by placing spark gaps across the condensers of the resonant network.

Low current thousand-volt supplies

For the operation of Geiger counters (Section 5) and other laboratory apparatus, power supplies capable of providing constant voltages at potentials of the order of two or three thousand volts are necessary. Ordinarily, the current demanded of such a rectifier is very moderate—of the order of 1 ma. Common practice is to build a half-wave rectifier, using a neon sign lighting transformer because of its low cost and small bulk, and employing as rectifier tube the 879, which is the cheapest tube designed to withstand voltages of this order of magnitude. The maximum voltage across the tube is, of course, approximately twice the output transformer voltage.

Two simple high voltage supplies which operate from low voltage batteries and are suitable for use in light, portable counter circuits have recently been described. Fig. 4 shows the circuit of a power supply due to Huntoon,[3] which is capable of supplying an output voltage of 600 v

[2] Garstang, *Electronics*, p. 50, Feb., 1932; Cockcroft and Walton, Proc. Roy. Soc. **A129**, 477 (1930).

[3] Huntoon, Rev. Sci. Inst. **10**, 176 (1939).

when it is operated from a 45-v battery. The breakdown voltage of the 32 tube used as rectifier limits the output voltage that may be obtained from such a unit to about 2500 v, the input voltage required being 180 v. The output condenser C_3 must, of course, be able to stand the output voltage.

The first two tubes constitute a multivibrator circuit (Section 6) in which the coupling of the second tube to the first is achieved by the resistor R_4 in the screen circuit of T_2. The square wave form characteristic of the multivibrator is responsible for the operation of the circuit; while T_2 conducts, current builds up in the inductance L, and the sudden stopping of current in T_2 produces a large positive voltage pulse across L. The rectifier tube T_3 permits the charging of the output condenser C_3 by means of successive pulses produced at regular intervals by the multivibrator.

Kaiser[4] has described a simple oscillator-rectifier unit which employs a pair of type 30 tubes to give voltages up to about 1400 v.

Stabilizing circuits

The need for constancy in the voltage output of electron-tube rectifiers is often very severe; to cite a single example, the sensitivity of a proportional multiplication counter (Section 5) is strongly dependent upon the supply voltage, so that elimination of fluctuations greater than about $\frac{1}{10}$ percent is desirable. A variety of electron-tube stabilizer circuits are described in

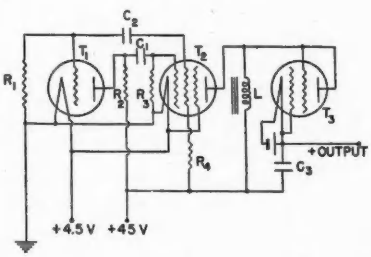


FIG. 4. Portable high-voltage supply: $R_1=0.3$ megohm; $R_2=25{,}000$ ohms; $R_3=0.25$ megohms; $R_4=12{,}500$ ohms; $C_1=C_2=0.02\ \mu f$, 200 v; $C_3=1\ \mu f$, 600 v; T_1=Type 30, T_2=Type 34, T_3=Type 32; L=Trutest audiotransformer No. 1619, primary and secondary in series-aiding. [These circuit constants are those given by Huntoon.[3]]

[4] Kaiser, Rev. Sci. Inst. **10**, 218 (1939).

the literature. Hunt and Hickman[5] have given an extensive discussion of the design and behavior of electronic voltage stabilizers. These authors find that all the voltage stabilization circuits in the literature, together with some invented by them, can be classified among four types, according to this derivation from (*a*) the transconductance bridge, (*b*) the amplification factor bridge, (*c*) the simple degenerative amplifier and (*d*) combinations of the foregoing, or circuits employing amplified control voltages. In any such stabilizer circuit, the voltage to be maintained constant is kept in constant ratio to a reference voltage, which may be supplied either by dry cells or by a gas discharge tube in which advantage is taken of the constancy of the "normal" cathode potential drop. Ordinary neon lamps with the series resistor removed are often

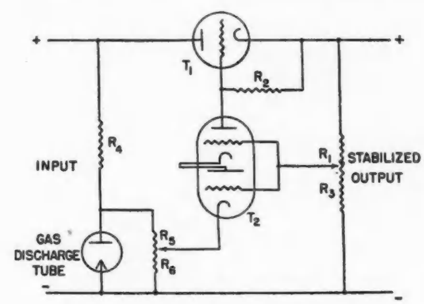


FIG. 5. Voltage-stabilizing circuit.

satisfactory for this service, if properly aged; special voltage-regulator tubes, such as the RCA 874 or the Western Electric 313-A, are preferable. The stabilization is, of course, only as accurate as the constancy of this reference voltage. Circuits derived from classes (*a*) and (*b*) are suitable when the stabilizer is designed either for constant-load or for no-load service; an example is the well-known circuit due to Street and Johnson,[6] which is derived from the amplification-factor bridge.

When the stabilizer is to provide a variable-load current, or when a continuously adjustable output voltage is desired, the internal resistance

[5] Hunt and Hickman, Rev. Sci. Inst. **10**, 6 (1939).

[6] Street and Johnson, J. Frank. Inst. **214**, 155 (1932). Modifications of this circuit have been described by Evans, Rev. Sci. Inst. **5**, 371 (1934), and Gingrich, Rev. Sci. Inst. **7**, 207 (1936).

of the stabilizer becomes important and must be kept as low as possible. Circuits of low internal resistance and high stabilization ratio may be derived from the basic degenerative amplifier. The stabilization ratio is the ratio of the change in input voltage to the induced change in output voltage across the load. A design which Hunt and Hickman[5] found very successful is shown in Fig. 5. A tube such as the 2A3 is best suited for use as stabilizing tube T_1 because of its large plate current at low voltage drop. The tube T_2 may be a pentode such as the 6J7, although the one indicated in Fig. 5 is a dual triode such as the 6C8G in the unconventional connection named the "cascode" by Hunt and Hickman. The amplification constant of the cascode may be shown quite simply to be $u_2 = u_a + u_b + u_a u_b$, where u_a and u_b are the amplification constants of the individual triodes. Used in this way the 6C8G appears to have a value for u_2 of about 1300 and a plate resistance of from 3 to 5 megohms. If the input voltage rises the plate current of T_2 increases, lowering the grid potential of T_1 so that a larger portion of the voltage drop appears across that tube than across the load. Also, if the load resistance drops, tending to draw more current, the grid of T_2 becomes more negative, reacting on the grid of T_1 in such a sense as to permit that tube to supply a larger current to the load. The linear analysis of the circuit is as follows:

$$\begin{aligned} i_{p1} &= s_1 e_{g1} + k_1 e_{p1}, & i_{p2} &= s_2 e_{g2} + k_2 e_{p2}, \\ e_{p1} &= e_i - (i_{p1} - i_{p2}) R_e, & e_{p2} &= (i_{p1} - i_{p2}) R_e - i_{p2} R_2, \\ e_{g1} &= -i_{p2} R_2, & e_{g2} &= (i_{p1} - i_{p2}) R_e a, \end{aligned}$$

where the symbols have their usual meanings; e_i is the incremental input voltage, R_e is the resistance of the load including $R_1 + R_3$ in parallel, and a is the ratio $R_3/R_1 + R_3$. Solving these equations for $R_e(i_{p1} - i_{p2})$, which is the output voltage e_0 across the load, we find the stabilization ratio $s_0[=e_i/e_0]$ to be

$$s_0 = 1 + (r_{p1}/R_e) + (a u_1 u_2 R_2 / r_{p2}) + R_2(1 + 1/s_1 R_2)(1 + 1/a u_2).$$

This may be made very large. In practice, Hunt and Hickman find values from 50 to infinity. Similarly, the effective internal resistance that the stabilizer presents to the load can be shown to be $r_{p1}/[s_0 + (r_{p1}/R_e)]$, and can be made as small as 1 or 2 ohms. This performance is comparable with that of a battery of lead storage cells of 15 amp-hr capacity. The magnitudes of the resistances in the circuit must be adjusted to produce the proper quiescent voltages for the tubes chosen and to suit the conditions that the stabilizer is to meet in practice.

2. Amplifiers

In almost every branch of physics it becomes necessary at one time or another to detect and measure very small electromotive forces or the small currents to which they generally give rise. "Small current" is, of course, a relative term, as we tend to judge current magnitudes in terms of the motion produced in the typical D'Arsonval system that forms the basis of practically all of our meters. Portable rugged meters of this type rarely have a full-scale reading of less than 10^{-4} amp, and currents less than this might be considered to be "small." However, double pivot instruments are available with sensitivities as high as 5×10^{-8} amp/div, and less robust meters of the semi-suspended type go to 5×10^{-9} amp/div. Fully suspended galvanometers which have lost the portable feature have standard sensitivities as high as 10^{-11} amp/div. Beyond this point the currents become too small to be measured by this method, though 10^{-11} amp corresponds to 6×10^7 electron/sec. No system of amplification will enable us to measure really small currents, in the sense of a few electrons per second, but systems have been devised that will detect the existence of currents of the order of 10 electron/sec, and currents as large as 10^3 electron/sec can be said to be measured by amplifying devices.

The measurement of small electromotive forces frequently presents the same problem as the measurement of small currents. If they are developed in low resistance circuits, no system of amplification will improve on the galvanometer, for this instrument can detect electromotive forces of the order of 10^{-7} v, which is about a hundred times better than any vacuum tube device. However, if the emf is developed in a high resistance circuit (high in comparison with the resistance of any available galvanometers) the vacuum tube begins to have advantages. In the special case, however, when the current or emf producing it is of a pulse or periodic type, the

vacuum tube amplifier almost invariably possesses advantages, for then a number of units can follow one another in cascade leading to very large over-all amplification. It is not possible to cascade more than two or, at the most, three units for direct current amplification, owing to the slow variations in the many factors entering a vacuum tube circuit whose effects obscure the direct or slowly varying current to be amplified.

It is convenient, therefore, to consider two classes of amplifiers for laboratory work: (1) those for measuring constant or slowly varying currents; (2) those for measuring pulses or periodic currents. The vacuum tube may be thought of as a device for measuring the potential difference between its grid and cathode, and the magnitudes of currents are inferred from a knowledge of the resistance or impedance of this grid circuit. Strangely enough, this situation is the opposite of that for the galvanometer, which is supreme in the potential measurement field; it measures currents directly and permits the inference of electromotive forces from a knowledge of the circuit impedance. The smallest change in grid potential that can be detected under the most favorable conditions is of the order of 10^{-5} v; hence, the smallest current that can be detected is $10^{-5}/R$, where R is the effective resistance presented by the grid and any shunting resistance. The limit to vacuum tube amplification that is implied by the previous statement is due to the random fluctuations in the plate current generally called "noise."[7] This can have its origin in any part of the circuit. Certain sources of noise are avoidable; for example, a.c. hum due to alternating current cathode heating, vibration, poor insulation or contacts and faulty resistances. These can be eliminated by using direct current for heaters, by selecting tubes of rugged construction with low microphonic characteristics, by using rubber vibration insulation and high quality electrical insulation, by carefully soldering all connections with rosin flux and, finally, by choosing good wire-wound resistances in critical circuit positions. The other type of noise which is unavoidable may arise from either of two sources and sets the real limit to amplification. One source is the random thermal motion of the conduction electrons in a resistor. The mean square random voltage $(V^2)_{\mathrm{Av}}$ appearing across the output terminals of an amplifier due to a grid circuit of resistance R and temperature T is given by[8]

$$(V^2)_{\mathrm{Av}}=4kT\int_0^\infty RG^2d\nu, \tag{1}$$

where k is the Boltzmann constant, G is the voltage gain of the amplifier and ν is the frequency over which RG^2 is integrated. This source of noise sets the limit to a.c. amplification. In d.c. amplifiers the frequency range amplified can be made negligible, and the ultimate noise arises from the fact that the space current is carried by the cloud of discrete electrons leaving the cathode. This electron stream is subject to statistical fluctuations which give rise to a random noise exceeding that described by Eq. (1) in the case of tubes whose grids "float," that is, are not connected through a high resistance to the cathode. In this case, the mean square random output voltage fluctuation is proportional to the grid current. Hence the latter must be kept as low as possible to achieve the ultimate in amplification. Current to a negative grid is due to many causes, chief among which are residual gas, and photoelectric and secondary electron emission. These sources can be minimized by the use of special tube construction and of low potentials. The Western Electric D-96475 and General Electric FP-54, which are known as electrometer tubes, have been specially designed to have low grid currents, in the range from 10^{-14} to 10^{-16} amp. They are the best tubes available for the amplification of small currents. Because of its small volume, good insulation, and rigid structure, the RCA 954 is one of the best of ordinary commercial tubes for low current amplification. It has grid currents of the order of 10^{-12} amp, whereas, the larger standard receiving tubes have grid currents of the order of 10^{-10} amp.

Direct current amplifier circuits

The most complete account of direct current amplifier circuits using electrometer tubes has been given by Penick,[9] and the circuit shown in Fig. 6 is the one recommended by him. It is

[7] Johnson and Llewellyn, Nat. Bur. Stand. Tech. J. **14**, 85 (1935).

[8] Barnes and Silverman, Rev. Mod. Phys. **6**, 162 (1934).

[9] Penick, Rev. Sci. Inst. **6**, 115 (1935).

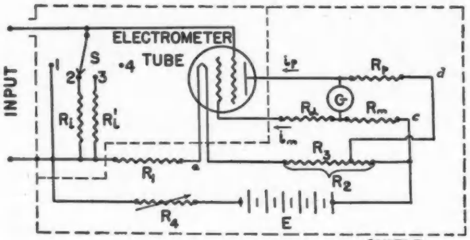


FIG. 6. Balanced electrometer tube circuit.

designed to reduce to a minimum spurious galvanometer deflection due to fluctuations in the battery voltage E. The space currents to the grid and plate depend on the potentials of the elements and also on the heater current. The resistances are disposed and their values chosen in such a way with respect to the tube characteristics that the total effect on the galvanometer current of a small change in battery potential is practically zero; the effects of the separate changes in the potentials applied to the tube elements nullify one another. Needless to say, the circuit must be constructed with wire-wound resistors and great care must be exercised to reduce all remediable sources of noise. It should be housed in a shielded metal container, and, for the best operation, the region surrounding the electrometer tube and the grid switch and resistors R_i should be in a rough vacuum. The switch S may be operated magnetically or by means of sylphon bellows. All grid insulation should be of the highest quality material, such as quartz, amber or lucite. During adjustment the switch should be in position *1* so that the grid potential remains fixed. Positions *2* and *3* correspond to desired values of grid resistors. S. S. White units with values as high as 10^{12} ohms may be used, but from 10^9 to 10^{11} ohms is generally a more useful range.

The following data apply to the W. E. D.-96475 type of tube. Since the space charge grid and plate are operated at the same potential in this tube, namely $+4$ v with respect to a, R_d of Fig. 6 is zero. The rated filament current is 0.27 amp and, as the control grid potential is -3 v, R_1 must have the value 11.1 ohms. The potential difference between the points a and c, E_{ac}, should be about 8.5 v; hence, if E is 12 v the variable resistance R_4 should have a maximum value of about 5 ohms. The value of 27.8 ohms is chosen for R_2, and the tap d is placed so as to make the potential E_{ad} about 5.3 v; that is, R_3 is approximately 16 ohms. The proper setting of R_4 may be determined by a milliammeter in the battery circuit; its resistance will be found to be about 3.7 ohms. A convenient value to choose for R_n is 10^4 ohms; R_p will then have a value of about 15×10^3 ohms. The proper values of R_p and R_3 are determined by successive approximation. First, with the galvanometer G disconnected and with milliammeters measuring the plate and grid currents i_p and i_n, R_p is adjusted so that $(E_{ad}-i_pR_p)=(E_{ac}-i_nR_n)$. On removing the meters and connecting the galvanometer the final adjustment is made in R_p so that the galvanometer remains at zero. Next, R_4 is changed by a small determinable amount (approximately 0.5 ohms), and the galvanometer deflection g_1 noted. The tap determining R_3 is then changed by a fraction of an ohm, and R_p is reset for balance after returning R_4 to its original value. The same alteration in R_4 is then made and the new galvanometer deflection g_2 is noted. If g_2 is less than g_1 the procedure is repeated, altering R_3 in the same sense. If g_2 is greater than g_1, R_3 is altered in the opposite sense until the deflection of the galvanometer is least and in the same sense for either an increase or decrease in R_4. When this adjustment is completed the circuit is balanced and ready for use. With a galvanometer having a sensitivity of 10^{-10} amp/mm an over-all sensitivity of 10^4 mm per grid volt can, in general, be attained. With an input resistance of 10^{11} ohms, this corresponds to a current sensitivity of 10^{-15} amp/mm. If the grid switch is set at position *4*, the grid is floating and the rate at which it acquires charge is measured by the rate of deflection of the galvanometer. Smaller currents can be measured in this way, but it is infeasible to attempt to measure currents much smaller than the natural grid current of the particular tube used.

One of the most useful direct current amplifiers for the range in which ordinary receiving tubes can be used has been devised by Vance.[10] This

[10] Vance, Rev. Sci. Inst. **7**, 489 (1936); Brumbaugh and Vance, Electronics **11**, 16 (Sept., 1938); Roberts, Rev. Sci. Inst. **10**, 181 (1939) (2 stage a.c. operated modification).

is a self-contained, rugged, accurate meter that is not damaged by overload and has a sensitivity of 10^{-10} amp/div with the highest grid resistance. The circuit is shown in Fig. 7. The input resistances shown are wire-wound units. Higher resistances of the S. S. White type can be employed to obtain lower current ranges, but at a sacrifice of accuracy. The circuit is essentially a three-stage direct coupled amplifier employing low filament-current tubes for dry cell operation. A separate battery supplies the plate of the last tube, and the plate current drop in the 12,000-ohm resistance in this circuit is returned to the first grid in the inverse-feedback sense; that is, an increase in space current in this tube makes the grid of the first tube more negative, tending to reduce the space current in the last tube. The inverse-feedback circuit composed of these three tubes with their associated batteries and resistors is essentially a device for maintaining automatically a constant potential difference between the cathode and control grid of the first tube. Any change in this potential, such as that which would be caused by a small current through one of the grid resistances, is automatically compensated by an equal and opposite change in potential across the 12,000-ohm load resistance. There is only unit voltage amplification, but this implies that the current amplification is equal to the ratio of the input to the output resistances.

The operation of the circuit may be seen more quantitatively by the following brief analysis. Let g be the voltage gain of the amplifier without feedback. Then $e_0 = ge_g$, where e_0 is the voltage change appearing across the 12,000-ohm resistance and e_g the voltage change made in the grid. If e_i is a voltage applied between the input and ground, the voltage change of the grid with inverse feedback is given by $e_g = e_i - e_0$. Eliminating e_g, we have

$$e_0 = \left(\frac{1}{1+1/g}\right)e_i.$$

Thus, for large values of g, e_0 equals e_i to within the fraction $1/g$. If g is of the order of 1000, as in the case of this circuit, e_0 equals e_i to within 0.1 percent. But e_0 appears in a circuit with a much lower resistance than e_i and, hence, it can be measured effectively with an ordinary D'Arsonval meter. A 100-μamp full-scale dial meter is shown in the circuit of Fig. 7. The input capacitor serves merely to by-pass any a.c. component reaching the meter terminals, and the high-pass filter to the grid of the last tube was found desirable to avoid oscillation. The potential drop appearing across the 12,000-ohm output resistance when the circuit is unexcited (no potential difference across the input resistances) is balanced by the 1.5-v battery in series with the meter. The potential of the grid of the first tube is adjusted to give a null reading with the circuit unexcited. One double pole switch is for turning the meter on; another is for checking the filament voltage; and the third is for reversing the polarity. The portability, ruggedness and permanent accuracy of this meter make it one of the most valuable pieces of general laboratory equipment.

Pulse amplifiers

The detection in a semi-quantitative way of the ionization produced in air or any other gas by a single particle is frequently desirable. The counter circuits of Section 5 are capable of detecting single ionizing particles, but they do not distinguish between particles producing different numbers of ions, except that a certain minimum number is necessary to set off the counter. If a potential change of 2×10^{-5} v is

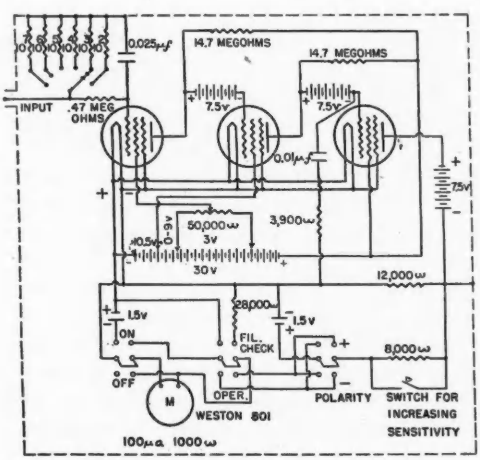


FIG. 7. Vacuum tube microammeter circuit [Vance].

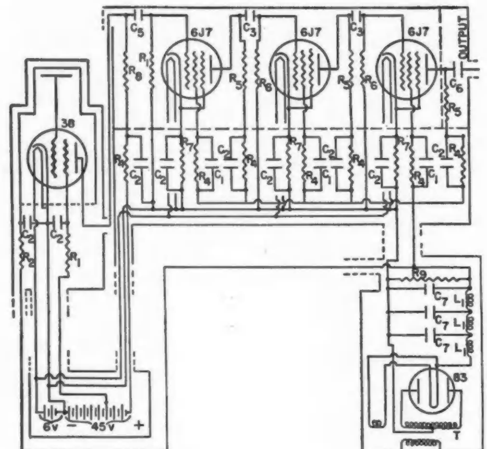


FIG. 8. Pulse amplifier: $R_1=0.25$ megohm; $R_2=10$ megohm; $R_3=2000$ ohms; $R_4=50{,}000$ ohms; $R_5=0.2$ megohm; $R_6=1$ megohm; $R_7=3500$ ohms; $R_8=0.1$ megohm; $R_9=50{,}000$ ohm; $T=$Thordarson transformer $T74R28$; $C_1=1$ μf; $C_2=2$ μf; $C_3=0.1$ μf; $C_4=4$ μf; $C_5=0.004$ μf; $C_6=0.005$ μf; $C_7=8$ μf; $L_1=8$ henry; $L_2=22$ henry. [These circuit constants are those given by Roberts.[11]]

taken as the minimum detectable at the grid of the first tube, and the grid and ion collector have together a capacitance of about 15 $\mu\mu$f, the least detectable charge is 3×10^{-16} coulomb or about 2×10^3 ions. Since α-particles produce about 4.0×10^3 ion/mm near the end of their path, the grid must be able to collect at least the number of ions produced by such a particle over 0.5 mm of path. This sets a lower limit to the depth of the ionization chamber that must be used at atmospheric pressure. Greater depths permit the detection of a smaller ionization per unit length. In order to detect the ionization produced by β-particles with this type of amplifier, a large fraction of the total path must contribute to the ions reaching the grid. In order to accomplish this, large chambers and high gas pressures are used.

In the design of a linear pulse amplifier, a compromise must be made between the ultimate sensitivity determined by noise and the fidelity of reproduction at the output of the pulse of ions reaching the input. If the amplifier is designed to pass a wide band of frequencies, a high fidelity can be achieved; but, by Eq. (1), the output noise is seen to be roughly proportional to the width of the band passed. On the other hand, a narrow passband decreases the noise but tends to distort the pulse. However, if the grid of the first tube floats, most of the noise originates in this grid circuit and, under these conditions, it is generally found desirable to have a rather wide band passed by the subsequent stages. The simplest standard cascade circuit for the uniform amplification of a wide band of frequencies is the resistance-capacitance coupled type. The principal requirement for the first tube is that it shall have a small capacitance and a low noise level. Probably the best tube for this purpose is the W.E. 259 B. The RCA 954 is nearly as satisfactory and its size makes it particularly suitable for close incorporation with the ion-collecting chamber. The remainder of the amplifier is of standard design with as high a voltage gain as feasible in view of the noise developed in its initial stage. The electrostatic shielding must be very complete and decoupling networks must be used in all stages.

The simplest and most inexpensive pulse amplifier that has been developed[11] is shown in Fig. 8. The internal shielding indicated by dashed lines is made of brass sheet, and all parts are assembled on this structure. The amplifier is then housed in standard radio cabinets indicated by the surrounding solid lines. Shielded leads run between the four units: (1) ionization chamber and first stage, (2) heater and first-stage batteries, (3) amplifier proper, (4) power supply. The ratio of the height of the pulse produced by a fast α-particle passing through a 2-mm chamber to the residual noise is 50. The output voltage pulse is 200 v. The total cost is low, and the amplifier can be used for detecting the ionization produced by α-particles, neutrons and protons.

General purpose a.c. amplifiers

There are innumerable applications in the laboratory for general purpose amplifiers throughout the audio- and radiofrequency ranges. The standard books on radio technic contain descriptions of circuits designed for special purposes. The most useful low power amplifier, however, is probably the one made up of simple

[11] Roberts, Rev. Sci. Inst. 9, 98 (1938).

resistance-capacitance pentode sections in cascade. It has the advantage of simplicity and high uniform voltage gain over a wide frequency range. Two sections can be operated from the same power supply without mutual interaction. If three or more sections are to be used, decoupling circuits should be employed in the plate leads, as indicated by dashed lines in Fig. 9. The tendency to low frequency oscillation (motorboating) can be eliminated by proper proportioning of the circuit elements, without unduly affecting the amplifier frequency characteristic. Circuit constants suggested by the manufacturer for three common pentodes are given in the legend. The value of the load resistance R_1, when considerably less than R_g, determines to a certain extent the maximum frequency passed without discrimination. This maximum is 5000 cycle/sec for $R_L=0.5$ megohm, and 20,000 cycle/sec for $R_L=0.1$ megohm. The other circuit constants are such that the voltage output at 100 cycle/sec is not less than $0.7E_0$, where E_0 is the uniform gain over practically the entire spectrum below the upper limit. If a smaller lower limit, say, f cycle/sec is desired, the values of the capacitances should be increased by the factor $100/f$. The cathode by-pass capacitance is to be considered as a minimum value. If a decoupling circuit is used, R_d is generally chosen to be about one-quarter of the

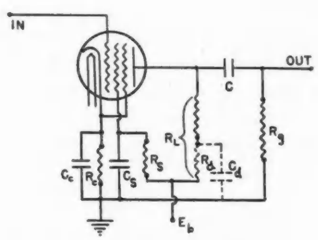


FIG. 9. Circuit and constants for resistance-capacitance coupled pentode units (6C6, 6J7, 57):

E_b (v)	3.00		600 (max.)	
R_L (megohms)	0.1	0.5	0.1	0.5
R_g (megohms)	0.5	2	0.5	2
R_s (megohms)	0.53	2.95	0.53	3
R_c (ohms)	600	2300	300	1500
C_s (μf)	0.06	0.04	0.08	0.05
C_c (μf)	8	4	10.5	4.5
C (μf)	0.006	0.0025	0.006	0.002
Peak voltage output across R_g at the current point	96	100	150	165
Voltage gain	94	240	112	352

total load R_L, and C_d should be from 0.25 to 1 μf.

In order to make effective use of these amplifier sections, the proper input and output devices must be employed. If the input circuit has a high resistance, such as a photo-tube or capacitance microphone, a resistance-capacitance circuit using the recommended values of R_g and C is most suitable. On the other hand, a photronic cell, carbon or magnetic microphone or pick-up, are low impedance devices and require a step-up input transformer. Manufacturers, such as The American Transformer Company, The Thordarson Transformer Company, or the United Transformer Company, have standard units designed for this purpose. An output transformer should also be used if the final circuit element has a low impedance. Frequently a larger amount of power is desired in the final stage to operate a speaker or meter, and for this purpose an additional power stage must be employed. The design of these units may be found in any standard text or may be obtained on request from transformer manufacturers. Their use in the radio and public address fields is so general that they are manufactured in quantity, and generally it is both cheaper and more satisfactory to buy an assembled unit than to build one in the laboratory.

3. Vacuum Tube Voltmeters and Null Indicators

The high input impedance of the vacuum tube adapts it to voltmeter application in high resistance circuits. Since a negatively biased grid draws no direct current, the grid terminal can be brought in contact with a circuit point without creating any disturbance in the previously existing circuit conditions, unless the added capacitance represented by the grid terminal is significant. For this reason it is advantageous to use a vacuum tube with a small grid capacitance and relatively low amplification constant in voltmeter circuits. Potentials of a few hundredths of a volt or less are best measured by one of the high-sensitivity a.c. or d.c. amplifier circuits of Section 2. Simpler circuits are available for measuring a.c. or d.c. potentials of 0.1 v or larger. Typical circuits and

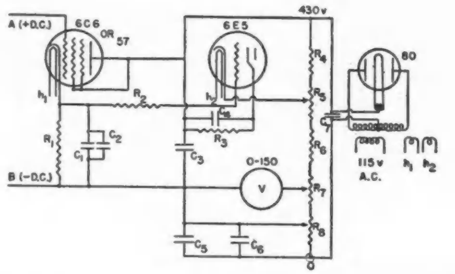


FIG. 10. "Magic eye" peak voltmeter: $R_1=2$ megohms; $R_2=0.1$ megohm; $R_3=1$ megohm; $R_4=10{,}000$ ohms (10 w); $R_5=1000$ ohms (wire); $R_6=500$ ohms (2 w); $R_7=200$ ohms (wire); $R_8=10{,}000$ ohms (10 w); $C_1=4$ μf (paper); $C_{2,3,5}=0.01$ μf (mica); $C_4=0.1$ μf (paper); $C_6=8$ μf (350 v); $C_7=16$ μt (500 v); V=high resistance voltmeter.

complete discussions of the principles of operation are available in vacuum tube and radio engineering textbooks. Nevertheless, there are two little known circuits of sufficient general laboratory utility to warrant brief descriptions.

Before proceeding to these descriptions, however, it should be mentioned that various types of voltage measurement are possible because, while d.c. potential measurement is unambiguous, with an a.c. wave the peak, average and rms voltages are simply related to one another only in the case of a pure sine wave. In general, a.c. waves contain harmonics, and in that case these three voltages are not related to one another. Vacuum tube circuits can be designed to measure any one of these that is desired. The "peak voltage" meter is generally of the so-called "push-back" type in which a d.c. potentiometer in the grid circuit of a tube biased to cut-off is adjusted until no positive signal (at the peak of the wave) reaches the grid. This d.c. voltage, which equals the positive a.c. peak, is read on a meter. The "average voltage" meter is constructed using a tube and circuit with a unilateral linear characteristic. The increment in plate current is then a measure of the average voltage of the applied a.c. wave. The "rms voltage" meter employs a tube, such as the 6D6 or 58, having an approximately parabolic characteristic. If the external circuit is designed to retain this characteristic, a meter in the plate circuit deflects in proportion to the rms value of the applied a.c. wave. The last type is in less common use than the first two.

A very simple rugged and inexpensive peak voltmeter can be constructed using a "magic eye" (6E5) tube as indicating device.[12] The 6C6 or 57 in Fig. 10 has such a large cathode resistor that it is practically biased to "cut-off." The variable contact on the bleeder resistor R_5 is adjusted until the "eye" is just closed (or in any other standard position) with the input terminals A and B connected together and the meter V at zero. If an a.c. potential then appears between A and B the "eye" opens, but it may be closed again by varying the potentiometer R_8 and the vernier R_7. After this adjustment the circuit currents are the same as before and, hence, the meter V reads the positive peak value of the a.c. wave. If a 6C6 is used, the reading of V will be low by about 1 v, and calibration is desirable for low voltage ranges. The dials of R_7 and R_8 may be directly calibrated and the meter eliminated. The various capacitances have by-passing functions only.

A meter of the "average voltage" type can be constructed using an RCA 954 pentode in the triode connection. This will measure voltages in almost any circuit with a negligible disturbing effect throughout the ordinary audio- and radio-frequency ranges. Though the tube characteristic itself is not particularly linear, the over-all characteristic of the circuit is rendered so by the presence of a large resistance in series with the cathode. This effect of the resistance may be readily seen from the fact that the incremental grid potential e_g is equal to the potential e_{g0} applied between grid and ground minus the plate-current drop in this cathode resistance. Elimination of e_g between this relation, $e_g=e_{g0}-R_c i_p$, and the equivalent plate circuit theorem,

$$i_p=[u/(R_l+R_p+R_c)]e_g,$$

yields

$$i_p=\{u/[R_l+R_p+R_c(1+u)]\}e_{g0},$$

where R_c is the cathode resistance, R_p the effective plate resistance and R_l that of the load in the plate circuit. As R_c and u are large, this expression reduces approximately to $i_p=e_{g0}/R_c$ from which u and R_p, the nonlinear factors, have disappeared. This is essentially the principle of the degenerative amplifier and it renders the scale linear over a very wide range.

[12] Waller and Richards, Radio Retailing, December, 1935.

The details of the circuit are shown in Fig. 11. The tube and small by-passing capacitors are mounted in a small metal container with the grid lead protruding. The leads from the tube run in shielded cable several feet long to the metal box housing the batteries, resistances and meters. The cathode resistors increase the linearity of the characteristic and provide two voltage ranges, 0–2 and 0–14 v. The larger cathode resistor produces a greater degenerative effect, thus decreasing the sensitivity and enlarging the voltage scale. The condenser C_2 is to insure there being no a.c. potential drop across the cathode resistors at low frequencies. With this precaution the device can be calibrated with a commercial frequency, and the reading will be practically independent of frequency through the audio and radio ranges. The resistance R_3 carries the normal plate current, which is low owing to the low plate voltage and the bias caused by the large cathode resistances. The drop between meter and tap on R_4 is equal and opposite to that in R_3 so that the meter does not deflect when the probe terminals are connected together. The resistances R_4 and R_5 are the coarse and fine adjustments of this potentiometer circuit. The battery in this circuit need not be greater than 10 v, though 22.5 v, being a standard value, is more readily obtained.

The null indicator for determining the balance point of an a.c. bridge may be considered as a special type of high sensitivity voltmeter or

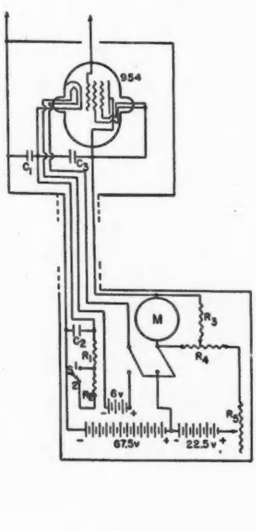


FIG. 11. High frequency vacuum tube voltmeter: $R_1 = 2000$ ohms (wire); $R_2 = 50{,}000$ ohms (wire); $R_3 = 10{,}000$ ohms (wire); $R_4 = 40{,}000$ ohms (wire); $R = 2000$ ohms (wire); $C_1 = C_3 =$ 500 $\mu\mu$f (mica); $C_2 = 16\ \mu$f (paper); M = microammeter (50 ohms); Position *1* of S, range 2 v; position *2* of S, range 14 v.

vacuum tube galvanometer. The headphones, which represent the simplest type of detector, cover only a limited frequency range efficiently and require comparative silence for successful use. If the highest sensitivity is desired they must, of course, be preceded by an amplifier.

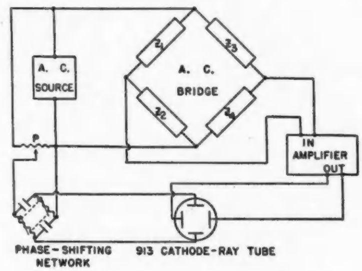


FIG. 12. Bridge-balance detector.

If the amplifier is followed by a rectifier meter or a "magic eye" tube in a detector circuit, a wider frequency range is available. These devices, however, are seldom as sensitive as the amplifier-headphone combination. A very sensitive balance indicator covering a wide frequency range has been proposed by Binns and Webb.[13] In this circuit the output of a resistance-capacitance coupled amplifier of the standard type across the bridge terminals unbalances a simple audio-frequency bridge, and the unbalance of this auxiliary bridge is detected. The frequency range available is from 25 to 70,000 cycle/sec, and it is claimed that a 5-μv rms output emf can be detected. Random output fluctuations are several times this figure, but a detection of 25 μv represents a high sensitivity. The complete detector is compact and completely a.c. operated.

A somewhat less sensitive but particularly convenient balance indicator employing a small oscilloscope tube (913) has been suggested by Lamson.[14] The balancing of any impedance bridge involves the separate adjustment of two controls to eliminate both the direct and quadrature components of the bridge output. In most commonly used bridges, such as the Schering type, these controls produce independent effects. The type of balance indicator suggested distinguishes between the effects produced by these

[13] Binns and Webb, Rev. Sci. Inst. **10**, 89 (1939).
[14] Lamson, Rev. Sci. Inst. **9**, 272 (1938).

controls so that they may be set independently to the balance point. This eliminates their alternate setting by successive approximations, which is frequently tedious. Also the fact that the two output components can be observed separately makes the detection of spurious disturbing effects somewhat simpler. The circuit is indicated in Fig. 12. An amplifier having a gain of about 80 db applies the output of the bridge to the horizontal plates of the oscilloscope tube. The amplifier should have a high selectivity against harmonics if the bridge balance is not independent of frequency. A 40-db selectivity against the second harmonic is recommended; a suitable amplifier for the purpose has been described by Scott.[15] Using 60 cycle/sec the device has a 100-μv sensitivity, which becomes somewhat poorer at higher frequencies. The circuits for the electron gun of the oscilloscope tube are not shown but are of the conventional type and may be built in the same unit as the amplifier and phase-shifting network. The a.c. sine-wave source supplying the bridge input is applied to the vertical plates through a potentiometer and the phase-controlling circuit. This is a simple bridge of two similar capacitors and two potentiometers ganged together. The reactance of the capacitors C should be large compared to the impedance of the a.c. source, and the resistances R should be large compared to the reactances C. This network is required to compensate for phase shifts in the amplifier so that the adjustment of the bridge output for phase—that is, the reduction of the quadrature component to zero—produces a straight-line pattern

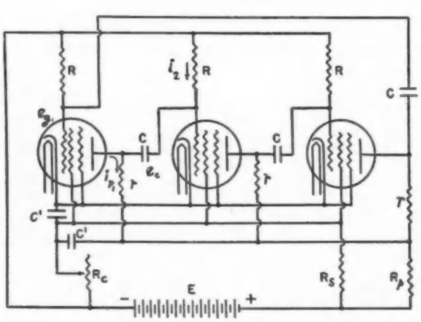


FIG. 13. Resistance-capacitance sine-wave oscillator.

[15] Scott, Proc. I.R.E. **26**, 226 (1938).

on the oscilloscope screen. This adjustment is made empirically and requires little subsequent alteration. After this setting has been achieved the direct and quadrature components of the bridge output can be balanced out separately. In the unbalanced state an arbitrary ellipse will appear on the tube screen. Varying the reactive control (quadrature component) of the bridge will reduce this to a straight line. Varying the resistive control (direct component) will rotate this line until it has a zero horizontal component.

4. Oscillators

The use of alternating or oscillatory currents is of such great importance in the power and communication industries that it has long formed one of the major divisions of electrical engineering. These essentially radio technics have also established themselves firmly among the laboratory arts of use to the physicist. One of the most important applications is in the measurement of time intervals. By making use of an efficient electromechanical oscillator, such as a quartz crystal, under carefully controlled conditions, a constancy of frequency of the order of 1 part in 10^6 can be readily obtained. The numerical value of this frequency can be determined through harmonic comparison or a chain of interlocking multivibrators (Section 6) relating it to a standard clock. If sufficient time is available, the value of the frequency may be determined to an accuracy compatible with the constancy. By means of these standard frequencies, time intervals of a wide range of durations may be measured with the accuracy of 1 part in 10^6. This is a higher accuracy than can be achieved in any other physical measurement except a fundamental measurement of length. Almost any type of oscillatory circuit can be adapted for use with a quartz crystal. Complete descriptions can be found in radio engineering textbooks, though it is frequently as cheap and more convenient to purchase the complete crystal and oscillator unit. In addition to interval measurement, oscillators in the audio- and lower radiofrequency ranges find many laboratory applications in the fields of acoustics, supersonics, driving ultracentrifuges, etc. For these purposes power oscillators may be used or the output of small oscillators may be increased

by power amplifiers. The study of the propagation of radiation in closed spaces, such as tubular conductors, is still almost as much in the field of physics as in that of electrical engineering, and for this purpose oscillators of very high frequency, 10^9 to 10^{10} cycle/sec, are required. Furthermore, there are a number of applications of radiofrequencies and also ultra-high frequencies, of the order of 10^9, in the field of atomic physics, as in the molecular beam technic of Rabi and his colleagues and in the study of the fundamental molecular vibration frequencies that occur in the range 10^{10} to 10^{11} cycle/sec. The generation of these ultra-high frequencies presents many special problems, and the various technics that have been suggested are still in the process of development.

Power frequencies up to about 1000 cycle/sec are usually produced by rotating electromagnetic machinery, but the thyratron inverter is assuming an important role. From the laboratory point of view, it has the advantage that the frequency can be varied over a comparatively wide range with little change in output. The low power, low frequency oscillator for the range 10^{-1} cycle/sec is difficult to construct with the usual capacitances and inductances, and a resistance-capacitance oscillator for this purpose will be described. It has certain elements in common with the multivibrator (Section 6) but produces a sine wave with little harmonic distortion. This type of oscillation is sometimes troublesome in standard resistance-capacitance coupled amplifiers. Oscillations with periods of 10 min or more can be generated, but in this range the time necessary for the establishment of the steady oscillatory state is of the order of a day. The standard types of audio-oscillators are extensively treated in all radio engineering textbooks. The beat frequency oscillator is the most convenient to use, as the entire range is available on one dial. It is more difficult, however, to obtain the stability of the simple oscillator. A recent circuit has been proposed by Hall;[16] but in view of the wide commercial use of these oscillators, they are generally cheaper to buy than to build.

One of the simplest and most convenient low-power oscillators through the range below 2×10^7

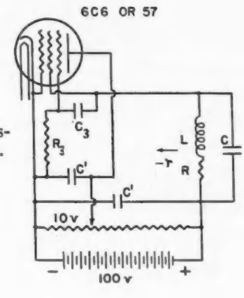


FIG. 14. Negative-transconductance oscillator.

cycle/sec is the negative-transconductance type or "transitron" due to Herold.[17] Additional data on this circuit in the foregoing range has been published by Brunette,[18] and the range can be extended upward to nearly 10^8 cycle/sec by the use of the RCA 954 acorn tube. The circuit can energize comparatively inefficient parallel oscillatory circuits, has good stability and good wave form. As this circuit is not as widely known as it should be in physics laboratories, it will be described briefly. Power oscillators producing several hundred watts in the neighborhood of 10^8 cycle/sec can be constructed in accordance with the manufacturer's specifications with standard tubes such as the 833, 834 and 888. At higher frequencies, 10^8 to 10^9 cycle/sec, magnetrons and the W.E. 316-A (door-knob tube) will produce about 10 w, and the RCA 955 (acorn tube) about 1 w or less. At still higher frequencies special magnetrons and special geometries for velocity modulation must be employed.

Resistance-capacitance oscillator[19]

A simple three-stage resistance-capacitance coupled pentode amplifier with the output returned to the input is shown in Fig. 13. The cathode bias resistor R_c, the screen resistor R_s and part of the plate resistor R_p are common for the three stages. These may be by-passed by capacitances C if the frequencies are sufficiently high to do this effectively. The interaction produced by one of these, say, R_c, is of value in insuring the generation of oscillations, and if R_c is adjustable some control of the magnitude is

[16] Hall, Rev. Sci. Inst. **10**, 38 (1939).

[17] Herold, Proc. I.R.E. **23**, 1201 (1935).

[18] Brunette, Proc. I.R.E. **25**, 1595 (1937); **27**, 88 (1939).

[19] Van der Mack and Van der Pol, Physica **1**, 437 (1934).

afforded. The value of R_c is determined by the cathode current and grid potential, and R_s is determined by the screen current and potential; $3R_p+r$ is determined by the plate current and potential. The frequency of oscillation is determined by R and C, and r is determined by the transconductance of the type of tube chosen. The simple linear analysis of the a.c. components in the grid circuit of the second stage yields

$$i_{p1}r+e_c+e_{g2}=0, \quad i_{p1}=s_pe_{g1}, \quad e_{g2}=Ri_2,$$

$$e_c=1/C\int i_2dt,$$

where the grid current is neglected, $R\gg r$, and s_p is the tube transconductance; that is,

$$s_pr\frac{de_1}{dt}+\left(\frac{d}{dt}+\frac{1}{RC}\right)e_2=0.$$

By cyclic permutation of the grid potentials the other two equations are obtained. The necessary condition for these three equations to have a solution is that the determinant shall vanish, and if the solution is to be undamped it will be found that the condition $s_pr=2$ must hold. Thus, if s_p is 1000 μmhos, r must be 2000 ohms. The period τ of this oscillation is given by $2\pi\sqrt{3}RC$ or about $11RC$. Thus, if R is 5 megohms and C is 11 μf, the period is 605 sec or about 10 min. The wave form is good if the amplitude of oscillation is kept fairly small by the proper adjustment of R and C. In setting up the circuit a shorter period should be used in order to ascertain whether the circuit is working properly.

Negative-transconductance oscillator

For a low plate voltage the coefficient of transconductance between the suppressor grid (grid No. 3) and the screen grid (grid No. 2) is negative; that is, if the suppressor grid is made more negative, a larger fraction of the electron space current is returned by it toward the cathode and a larger negative current is directed to the screen grid. If these grids are connected together by a condenser having a low impedance for the frequency concerned, grid No. 3 (to which there is no current) follows the potential of grid No. 2, and the effective a.c. resistance presented by the cathode and terminals of grid No. 2 is negative; that is, an increase in current in one direction tends to produce a still larger current in that direction. This unstable condition over the range in which it exists can be used to generate oscillations in a resonant circuit in parallel with the cathode and grid terminals. The ultimate source of power is the plate battery. Mathematically, this can be seen by considering a negative resistance, $-r$, in parallel with a capacitance C and coil of resistance R and inductance L. The condition that the total current to the junction shall be zero is $r=L/RC$, and this represents the smallest value of L/RC for which oscillations will be sustained. To generate oscillations in a low Q circuit—that is, one that absorbs power—the value of $-r$ should be as small a value as possible.

The circuit of Fig. 14 produces a particularly small negative resistance in parallel with the resonant circuit. Almost any standard pentode, such as the 57, 58, 6C6, etc., can be employed. The 59 can be used for larger powers, and the 954 for extending the frequency range upward. The value of r can be calculated from the tube resistances and transconductances. The only variable potentials are those of the second and third grids, C_{g2} and C_{g3}. Thus the variable component of the current to grid No. 2 can be written:

$$i_{g2}=(e_{g2}/r_2)+s_{23}e_{g3},$$

where r_2 is the resistance to this grid and s_{23} the transconductance between these grids. If the reactance of C_3 is small compared to the resistance of R_3, $e_{g2}\cong e_{g3}$ and

$$r=e_{g2}/i_{g2}=r_2/(1+r_2s_{23}).$$

For these pentodes $r_2s_{23}\gg 1$ and $s_{23}<0$, hence $r\cong 1/s_{23}$ and it is negative. This quantity can also be determined experimentally by knowing L and C and determining the largest value of R for which oscillations are sustained. The role of the plate in this circuit is simply the collection of electrons. The control grid (grid No. 1) can be used to determine the magnitude of the oscillations. An automatic amplitude-limiting circuit can be easily devised whereby the a.c. potential developed across C produces a unidirectional current through a rectifier and biasing resistance between the cathode and grid No. 1.

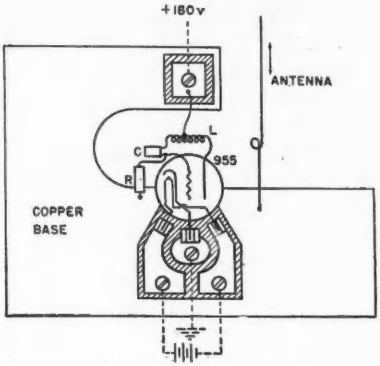


FIG. 15. High frequency oscillator.

If the amplitude is thus limited the wave form is improved. A small value L/C is also conducive to good wave form; this ratio should be kept less than 10^8 and preferably below 10^7. This condition and that for the existence of oscillation determine the frequency range that can be covered with one inductance. Taking $r=4000$ ohms, which is representative, and $R=5$ ohms for an air-core 0.1-h inductance, the conditions $L/10^8<C<L/RC$ allow C the range from 0.1 to 3 μf, or a frequency range of a factor of seven. For lower or higher frequencies a larger or smaller inductance must be used. A good value for R_3 is 1 megohm, and the capacitance C_3 need not be larger than 0.01 μf down to the lowest audio-frequencies. A value of 1 μf is satisfactory for the by-passing capacitances C'. This circuit is extremely simple and requires no adjustment after once being assembled. It has a large number of routine laboratory applications and presents many points of pedagogic interest.

Ultra-high frequencies

A number of tubes of more or less standard design such as the RCA 955, 833, 834 and 888, and W.E. 316-A are available for generating frequencies in the range 10^8 to 10^9 cycle/sec. Circuits for these tubes are supplied by the manufacturers. The circuit designs differ from those appropriate for lower frequencies because lengths of conductors and stray capacitances which are of negligible importance in the ordinary range become highly significant at these frequencies. Concentric lines are widely used as resonant systems and, if there is an opening of considerable angular aperture, they may be used as radiators. For details of this nature, however, reference should be made to the current literature. In addition to these tubes there is a standard magnetron, G.E. FH 11, covering the same frequency range. The circuits employing this tube are extremely simple but the additional expense and complication of the magnetic field are disadvantages. Full operating details are given in the manufacturer's instructions.

A simple low power oscillator using a 955 tube is shown in Fig. 15. The size of L depends on the frequency desired; about four turns of bare No. 14 wire on a mandrel the size of a pencil is satisfactory. The blocking condenser C should be physically small and of about 30 to 50 $\mu\mu$f capacitance. A grid leak of about 2×10^4 ohms is recommended. By-passing condensers of from 50 to 100 $\mu\mu$f are placed directly at the tube and plate supply terminals by fastening these to copper plates separated from the grounded copper base by thin sheets of mica. Ordinary forms of condensers lead to parasitic oscillations and loss of power. A small choke, consisting of one or two turns a few millimeters in diameter, may be necessary in the grid lead. Such an oscillator will generate about 0.5 w at 3×10^8 cycle/sec. The power output decreases rapidly at higher frequency. A loosely coupled quarter-wave radiator of adjustable length may be mounted as shown for radiation experiments.

No tubes are now available commercially for generating frequencies higher than 10^9 cycle/sec. Very small magnetrons in high fields have been used by Cleeton and Williams[20] for generating frequencies even higher than 10^{10} cycle/sec, which represents approximately the upper limit of this technic. The finite time that it takes for an electron to traverse the interelectrode space becomes the limiting factor in tubes of the more conventional type. Various experimental tubes in which the modulation of a cylindrical electron beam is used to generate oscillations have been reported.[21] The technic of employing a well-defined cylindrical beam of high-energy electrons passing down the axis of cylindrical electrodes of

[20] Cleeton and Williams, Phys. Rev. **44**, 421 (1933); **45**, 234 (1934).
[21] Hahn and Metcalf, Proc. I.R.E. **27**, 106 (1939).

very small geometry connected together to form the oscillatory circuit will doubtless be developed much further and may open the frequency region up to 10^{11} cycle/sec.

5. Electron Counter Circuits*

The pulse counter described in Section 2 is the most generally satisfactory device for the detection and measurement of individual densely ionizing particles, such as α-particles and protons. Such an amplifier is not adapted, however, to the detection of single electrons; for the specific ionization produced by a β-particle is too small (about 50 to 200 ion pair/cm in air under standard pressure, depending on the electron energy) to permit the detection, above the inevitable random noise in a high gain amplifier, of the voltage pulse caused by collection, on the grid of a vacuum tube, of the ions produced by a single β-particle in a chamber 1 or 2 cm deep.

The detection of single, swift electrons by their ionization is possible, however, in any of the many forms of multiplication counter. In such a counter, the number of primary ions produced by the ionizing particle is augmented by collecting the electrons initially set free in a field sufficiently strong so that each original electron itself produces ionization by collision with the atoms of gas in the counter, before its final collection on the anode. Two types of multiplication counter should be distinguished; in the first, the multiplication factor connecting the number of ions originally set free in the counter with the number finally collected is substantially constant, so that the size of a given pulse is a measure of the specific ionization of the particle producing the pulse. Such a counter is called a *proportional* counter. Since it is generally of no advantage to know the specific ionization of an electron, and since the amplification produced by ionization by collision is much smaller in the proportional form of multiplication counter than in the nonproportional type, the usefulness of the proportional counter is practically restricted to the detection of heavy particles. Because the multiplication factor of such a counter depends strongly on the voltage applied to its electrodes, and because the sensitive region inside the counter which a particle must enter to produce a count is often ill defined, the pulse amplifier already described is a more reliable and satisfactory device for the registration of heavy particles, and has practically supplanted the proportional counter for this purpose.

In the nonproportional counter, to whose use our remarks will be restricted, the production even of a single pair of ions will result in an avalanche of ionization whose magnitude is independent of the number of primary ions that initiated the discharge. The most widely used form of these counters is that due to Geiger and Müller.[23] A fine wire is stretched down the axis of a conducting cylinder and the pressure in the region between these electrodes is reduced to a few centimeters of mercury. A high, direct voltage is applied to the electrodes, the wire being made the anode. The detailed explanation of the action of the nonproportional counter is still a subject of active discussion. Enough factors influence the successful preparation of counters so that a great variety of empirical recipes for the production of satisfactory counters is to be found in the literature.[24]

The fundamental counter circuit is that shown in Fig. 16. The potential V is maintained at a value low enough so that a self-sustaining corona discharge will not take place in the counter, yet high enough so that the passage of an ionizing particle through the counter will initiate a discharge. Once begun, the discharge must be stopped as quickly as possible, so that the counter may be prepared for the registration of another particle. The function of the resistance R is to cause the extinction of the discharge by producing a voltage drop sufficient to render the difference of potential across the terminals of the counter too low to maintain the discharge. The current through the counter then abruptly stops, and the voltage across the counter terminals recovers exponentially to V with a time constant RC, where C is the capacitance to ground of the counter wire and its connections.

* For a very interesting and complete account of the construction of counter circuits and their use in an instructional laboratory, see the article by A. L. Hughes, Am. J. Phys. (Am. Phys. Teacher) **7**, 271 (1939).

[23] Geiger and Müller, Physik. Zeits. **29**, 839 (1928); **30**, 489 (1929).

[24] See, for example, Strong *et al.*, *Procedures in experimental physics* (Prentice-Hall, 1938), chap. VII.

It is in respect to the extinction of the discharge that good counters differ from bad ones. For a good counter, the resistance R may be as low as 10^4 or 10^5 ohms, with a correspondingly small time constant; while a poor counter will require an extinguishing resistance larger than 10^9 ohms. Clearly, the reliable counting rate will be 10^4 to 10^5 times slower if a poor counter is used in the conventional resistance extinguishing circuit. Neher,[24] Trost[25] and others have given

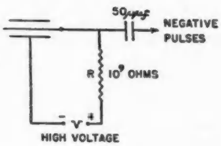


FIG. 16. Counter with resistance extinction.

directions for the construction of counters that are easily extinguished.

In recent years, several counter-extinguishing circuits employing vacuum tubes have been developed. These permit the use for fast counting of even a counter that is bad in the sense of the preceding paragraph. The most widely used of such circuits is that due to Neher and Harper,[26] which is shown in Fig. 17. The vacuum tube is a high u pentode with sharp plate-current cut-off, such as the 57, the 6C6, or the 6J7G. It is preferable not to use a metal tube in this service, since the full voltage V applied to the counter appears across the tube terminals. The breakdown voltage of the glass tube types is about 2400 v, while the metal 6J7 will withstand only about 1500 to 2000 v.

The action of the extinguishing circuit is as follows. The tube is biased to plate-current cut-off, so that no current exists when the counter is nonconducting. When the counter begins to conduct, owing to the passage of an ionizing particle through it, the current through R_1 makes the control grid less negative and permits the passage of plate current in the tube. The large voltage drop produced in R_2 by this plate current extinguishes the counter discharge, causing the grid potential of the tube to return to its cut-off value, whereupon the plate current stops and the circuit recovers itself in a time that is short because of the small resistances and capacitances of the circuit. The size of the resistor R_2 is seen to depend upon the vacuum tube characteristics; a value of 1 or 2 megohms is generally satisfactory. The grid resistor R_1 must be chosen to be of suitable size for the counter employed; a large counter may operate satisfactorily when $R_1=1$ megohm, while a counter 1 in. in length and $\frac{1}{4}$ in. in diameter requires a grid resistance of about 50 megohms. The grid voltage E_g must be adjusted to a value which is neither so far negative that the counter pulses do not produce sufficient plate current to extinguish the counter —a condition called "blocking" by Neher and Harper—nor so little negative that plate-current cut-off in the tube has not been reached, and the resulting drop in voltage across R lowers the counter voltage below the threshold voltage where counting begins. In general it is quite easy to determine the proper value of E_g by listening with headphones to the pulses produced by the circuit. The best value of E_g will be about -5 to -6 v for the circuit constants shown, if the voltage applied to the counter is about 100 v above the threshold for the counter used.

A modification of this circuit has been used by Neher and Pickering.[27] It avoids the need for a variable control grid bias and has certain other advantages, which for many applications are outweighed by the disadvantages that a constant current drain is made on the high voltage supply and that the entire extinguishing tube and its power supply must be insulated from ground to withstand the full counter voltage. Another vacuum tube extinguishing circuit employs a biased multivibrator (Section 6) to quench the counter discharge.[28] The chief advantage of this circuit is that its resolving time depends only on the circuit constants and is independent of the particular counter used. Its disadvantages are that two tubes are required in the extinguishing circuit and that the a.c. coupling which produces the quenching action may fail to respond when a continuous corona discharge has been set up in the counter.

[25] Trost, Zeits. f. Physik **105**, 399 (1937).
[26] Neher and Harper, Phys. Rev. **49**, 940 (1936).
[27] Neher and Pickering, Phys. Rev. **53**, 316 (1938).
[28] Ruark and Brammer, Phys. Rev. **52**, 322 (1937); Getting, Phys. Rev. **53**, 103 (1938); Ruark, Phys. Rev. **53**, 316 (1938).

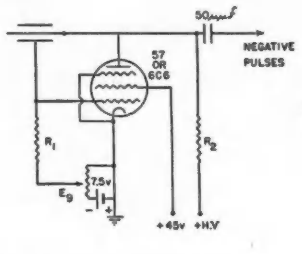


FIG. 17. Neher-Harper circuit.

Coincidence counting

One of the most powerful technics afforded by the counter is that of coincidence counting. A circuit may be arranged in such a fashion that pulses are recorded only when they occur simultaneously in two, three, or more counters, which may be placed in any positions relative to one another, or may even be arranged so that they respond preferentially to different types of radiation, as in the celebrated experiment of Bothe and Geiger.

While a number of circuits have been proposed for coincidence counting, the one in widest use at present is due to Rossi. It is shown in Fig. 18. Each counter employed in the coincidence arrangement is connected to an extinguishing circuit like that of Fig. 17, the output of which is a negative voltage pulse for each discharge of the counter. The negative pulses from each extinguishing circuit are applied to the grid of a high μ pentode with sharp plate-current cut-off, such as the 57, the 6C6, the 6J7, or the 6J7G. The fixed potential of the pentode control grid is zero, so that the resistance of the tube is low in the absence of a pulse. The magnitude of the negative voltage pulse received from the counter and extinguishing circuit is sufficient to swing the tube to cut-off. However, the plates of the pentodes are all connected in parallel, and to the plate voltage supply through a common resistor R. The voltage drop across any of the pentodes, in the absence of a pulse, is small compared with the drop across R, so that, even though the plate current is cut off in one tube, the voltage change at the output will be small. If each of the grid resistors R_g in Fig. 18 is 0.25 megohm, and the plate resistor R is 0.1 megohm, for a plate voltage of 300 v and a screen voltage of 100 v, the plate resistance of a 6J7 tube will be about 5000 ohms. Under these conditions, the fourfold coincidence circuit of Fig. 18 will give an output pulse of about 1.2 v if one counter discharges, 3.6 v if two discharge simultaneously, 10.6 v for a threefold coincidence, and practically the full plate voltage for a fourfold coincidence. The recording stage (Section 6) may readily be adjusted to respond only to the large voltage pulses which mark fourfold coincidences.

Of course, the words *coincidence* and *simultaneously* as used here have meaning only in terms of the finite resolving time of the circuit. Since the pulses from each counter have a finite duration, two pulses arriving within a short time of each other may be regarded by the circuit as coincident, even though they may not be causally related. A good discussion of the accidental coincidences arising in counting circuits has been given by Eckart and Shonka.[29]

6. Scaling Circuits and Allied Devices

The mechanical recording of the voltage pulses produced by the pulse amplifier described in Section 2 or the counter circuits described in Section 5 may, for low counting rates (less than about 300 random counts/min) be accomplished by a circuit such as that shown in Fig. 19, which employs a rapid mechanical counter operated

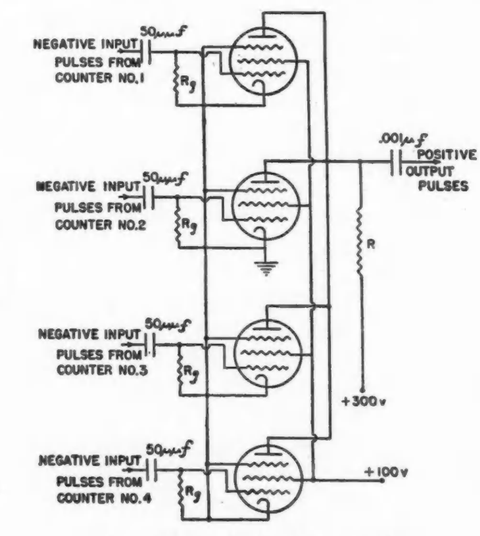


FIG. 18. Rossi coincidence circuit.

[29] Eckart and Shonka, Phys. Rev. **53**, 752 (1938).

by a single self-extinguishing gas-filled relay tube, or thyratron. The circuit constants shown are suitable for the argon-filled 885 and the high-impedance model of the "Cenco Impulse Counter."[30] It should be observed that positive pulses are required to operate the recording circuit shown, while negative pulses are provided by a counter and a Neher-Harper extinguishing circuit. In such a case, the sign of the pulses should be reversed by a stage of resistance-capacitance coupled amplification interposed between extinguishing circuit and recorder. The rate at which coincidences between several counters are recorded is ordinarily low enough so that the simple recording circuit of Fig. 19 is satisfactory; in this case, the adjustable negative grid bias on the 885 may be set to discriminate against the small pulses representing coincidences among part of the counters, only the large pulses arising from coincidences among all the counters swinging the grid of the thyratron far enough toward zero to cause it to fire.

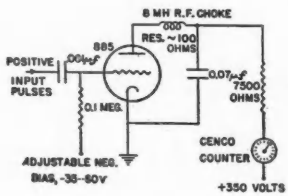


FIG. 19. Recording circuit.

Frequently, the counting speed provided by a single-tube recorder is insufficient, the fixed resolving time of the mechanical recorder limiting the counting speed of the entire arrangement. Under these circumstances, it is customary to use a scaling circuit which delivers only every nth count to the mechanical recorder. The improvement in permissible counting speed made possible by such a scaling circuit is more than n-fold; for not only is the average time between pulses increased n times, but the regularity with which the pulses are delivered to the counter is greatly improved.

The customary scaling circuits are derived from two-tube trigger circuits which possess two stable conditions: one in which the first tube is conducting and the second tube carries no current, and another in which these functions are reversed. The parallel thyratron switching circuit is such a device, and is the basis of the familiar scale-of-2^n scaling circuit. Fig. 20 shows the scale-of-two unit from which scaling circuits of higher

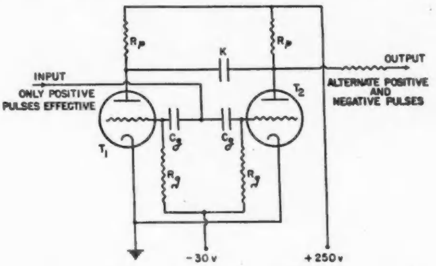


FIG. 20. Thyratron scale-of-two circuit.

ratio are constructed. Suppose that initially tube *1* is conducting and tube *2* is not. Then the potential at the anode of tube *1* is about +15 v, the voltage drop in the 885 being practically constant at this value while the tube is conducting. The full plate-supply potential appears at the anode of tube *2*. The application of a positive pulse to the grids of both thyratrons through the condensers C_g has no effect on tube *1*, but it may swing the grid of tube *2* far enough in the positive direction to cause the tube to fire. The potential at the anode of tube *2* then suddenly drops from +250 v to +15 v, passing a large negative pulse through the condenser K to the anode of tube *1*. The current in tube *1* is stopped momentarily when the anode becomes negative, and the negatively biased grid regains control, so that the current in tube *1* does not start again. The next positive pulse will fire tube *1* and extinguish tube *2*, and so on. If the anode lead of one of this pair of thyratrons is connected to the input of another similar pair, pulses that are alternately positive and negative will be passed on from the first pair to the second. Since the second pair responds solely to positive pulses, only every second pulse entering the input of the first pair causes the second pair to switch. If the output of the second pair is coupled to the recording circuit of Fig. 19, only every other pulse from the second pair will be recorded, as the recording circuit itself responds only to positive pulses. Every fourth impulse applied to the input of the first pair is then recorded, and the arrangement

[30] Central Scientific Co., Cat. No. 73510.

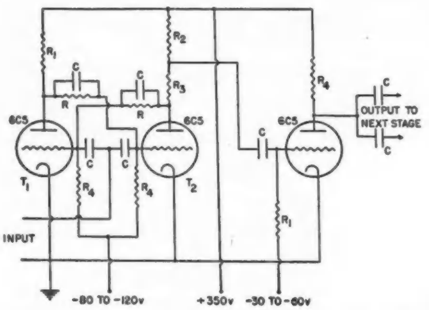


FIG. 21. Vacuum tube scaling circuit: $R=400,000$ ohms; $R_1=50,000$ ohms; $R_2=30,000$ ohms; $R_3=20,000$ ohms; $R_4=100,000$ ohms; $C=25$ $\mu\mu$f.

constitutes a scale-of-four. Details for the construction of a scale-of-eight employing thyratrons have been given by Giarratana.[31] The magnitude of the pulses to which the scaling circuit will respond may, of course, be fixed by adjusting the negative grid bias on the first pair.

The limiting speed with which pulses may be handled by the scaling circuit just described is set by the deionization time of the 885; if the negative pulse through K does not keep the grid of the tube which is to be extinguished negative for a time longer than the de-ionization time, the grid cannot regain control, while the circuit cannot respond to another pulse during the time the anode is negative. The use for scaling of a trigger circuit employing vacuum tubes avoids this difficulty. Such a trigger circuit is shown in Fig. 21; it was invented by Eccles and Jordan and adapted for scaling circuit use by Lifschutz and Lawson.[32] Suppose, for a moment, that equal currents exist in the two tubes. Any increase in the plate current of tube *1* makes the grid of tube *2* more negative, which produces a decrease in the plate current of tube *2*. This makes the grid of tube *1* more positive, increasing the plate current of tube *1* further, and so on. This process continues until tube *2* has been driven to plate-current cut-off. The circuit is stable with either tube conducting and the other tube cut off. The circuit may be caused to transfer from one stable condition to the other by the application of a pulse of either sign to the grids of the tubes, provided the pulse is large enough in magnitude to initiate the transfer action.

Since the trigger circuit responds as well to negative as to positive pulses, it is necessary to provide rectification between stages, as shown in Fig. 21, to eliminate the negative pulses which alternate with positive ones from each scale-of-two unit. It is not necessary, of course, to provide a final rectifier if the output of the scaling circuit is fed to the thyratron recording circuit of Fig. 19. Further design considerations will be found in the paper of Lifschutz and Lawson.[32]

The multivibrator circuit, mentioned in Sections 1 and 4, is like the trigger circuit of Fig. 21, except that the direct coupling provided there by the resistances R is replaced by a.c. coupling achieved by substituting condensers for these resistances. The small condensers shown in Fig. 21 shunting the resistors R are merely for speeding the response of the trigger circuit when it is used for scaling. The input capacitances connecting the grids in the figure are, of course, omitted from the multivibrator circuit. A more detailed description of the functioning of the circuit, as well as its more familiar application, will be found in the literature.

Electronic frequency meters

Either of the two scaling circuits just described may be used as the basis of a compact, simple, direct-reading frequency meter for the audio-frequency and low radiofrequency ranges. Fig. 22 shows a frequency meter described by Hunt[33]

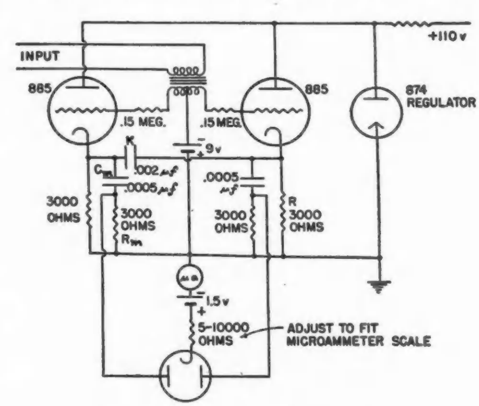


FIG. 22. Vacuum tube frequency meter.

[31] Giarratana, Rev. Sci. Inst. **8**, 390 (1937).

[32] Eccles and Jordan, Radio Review **1**, 143 (1919). Lifschutz and Lawson, Rev. Sci. Inst. **9**, 83 (1938).

[33] Hunt, Rev. Sci. Inst. **6**, 43 (1935).

and suitable for the range from about 100 to 10,000 cycle/sec. This device is based on the parallel thyratron switching circuit, the extinguishing condenser K being connected between the cathodes of the thyratrons, instead of between anodes as in Fig. 20. This change is made to secure pulses of positive sign. A pulse of current is passed through the diode and the meter by way of the condensers C_m at each switching operation of the circuit. If the time constant R_mC_m of the metering circuit is kept lower than that, RK, of the switching circuit, there is no danger that at high input frequencies the pulses delivered to the metering circuit will overlap. In the absence of overlapping, the average current through the meter is a direct measure of the frequency of the input signal. Interesting advantages of this circuit are: (*a*) the reading of frequency is independent of wave form of the input signal, provided the algebraic sign of the input voltage does not reverse more often than twice during each fundamental period; (*b*) the output is independent of the amplitude of the input signal, provided the signal is great enough to operate the meter; (*c*) the frequency reading does not depend upon uniform spacing of the input pulses, so that the frequency meter may be used as an average-counting-rate meter for very high speed counting of randomly distributed pulses. The general laboratory utility of such a direct-reading frequency meter is very great. It should be clear that, with appropriate modifications, the hard tube scaling circuit already described can serve as a similar type of frequency meter.

The First Explanation of Interference

I Bernard Cohen
Carnegie Institution of Washington, Division of Historical Research, Cambridge, Massachusetts

THE principle of interference is usually associated with the name of Thomas Young (1773–1829), who invented it as a means of explaining the phenomenon of Newton's rings on the basis of the wave theory of light. The complete story of the steps leading up to the invention of this principle is, however, far from simple and forms a rather curious chapter in the history of science.

In the first place, the phenomenon was not discovered by Newton; the rings had previously been observed and described by both Boyle and Hooke. Second, although they bear his name, the rings were not satisfactorily accounted for by Newton. Third, the principle of interference, invented by Young to account for the rings, was the first major step toward the overthrowing of the eighteenth-century reign of the corpuscular theory of light. In fact, it constituted the first major theoretical discovery in optics in about a hundred years. In the hands of Young and Fresnel, the principle became a powerful enough bludgeon to establish on a firm basis, for the nineteenth century at least, the idea that light was an undulatory phenomenon. It is curious that the phenomenon whose explanation demanded the principle was named after Newton, who was considered during the eighteenth century to be the great champion of the corpuscular theory. It may be noted, moreover, that in many laboratory courses in elementary physics, Newton's rings are employed today as a simple means of determining the wave-length of light.

There are other interesting aspects to the story, not the least curious of which is the example of Christiaan Huygens (1629–1695) who wrote the first important treatise on optics from the point of view of the wave theory. In it[1] he

[1] *Traité de la lumière où sont expliquées les causes de ce qui luy arrive dans la réflexion et dans la réfraction. Et particulièrement dans l'étrange réfraction du cristal d'Islande. Par C. H. D. Z.* [Christiaan Huygens de Zuylichem] (Leyden, 1690). This treatise was written 12 years before it was published and communicated to the Académie Royale des Sciences (Paris) in 1678. The delay was caused by a desire on the part of the author to translate it into Latin, a desire that was never realized. It may be conveniently obtained in an English translation by S. P. Thompson (Macmillan, 1912), to which edition all future references will be made. Extracts, containing his statement of the principle, appear in Magie, *A Source Book in Physics* (McGraw-Hill, 1935), p. 283, which also contains excerpts from the optical papers of Young, Fresnel and Newton.

announced the famous principle that bears his name, by means of which he was able to explain reflection and refraction in a most satisfactory manner. He also attempted to explain double refraction in uniaxial crystals such as Iceland spar, or calcite, by the assumption that, within the crystal, the wave surface was a sphere and a spheroid. This was the first attempt to explain this unusual phenomenon which had been described for the first time by Erasmus Bartholin (1625–1698) some few years earlier.[2]

Since, according to Huygens' principle, each element of a given wave surface is a new source of disturbance, so that a wave front at any posterior time is the envelope of wave surfaces constructed on these little elements as centers, it may be thought that it should follow simply that at any point on such a wave envelope the disturbance is the vector sum of the disturbances due to these little elements. This is not really the case. In fact, had Huygens followed such an idea, he would have been able to eliminate the vital weakness in his presentation. For, as Mallik[3] has pointed out so clearly, if he had seen the possibility of this idea, he would have been "led to the proof of the rectilinear propagation of light, but it was not till quite a hundred years later that this was successfully accomplished by Young and Fresnel. For . . . this is in reality the principle of interference."

But there was one important factor that prevented Huygens from arriving in any such fashion at the principle of interference; he denied periodicity to his waves. In the theory that he advanced,[4] he considered light to be composed of pulses transmitted longitudinally by means of the impact of one elastic "ether-molecule" upon another, relying in great part on the analogy with sound waves. To these pulses of light that went forth in all directions, Huygens denied periodicity precisely because he wished to avoid interference of any kind. For example, he says at the very beginning of his treatise (p. 2) that he intends to show "how visible rays, coming from an infinitude of diverse places, cross one another without hindering one another in any way." Later on in the first chapter (p. 17), he says:

THOMAS YOUNG

Engraved by G. R. Ward from a painting by Sir Thomas Laurence. Frontispiece to George Peacock, *Life of Thomas Young* (John Murray, 1855).

> But as the percussions at the centres of these waves possess no regular succession, it must not be supposed that the waves follow one another at equal distances: and if the distances marked in the figure appear to be such, it is rather to mark the progression of one and the same wave at equal intervals of time than to represent several of them issuing from one and the same centre. After all, this prodigious quantity of waves which traverse one another without confusion and without effacing one another must not be deemed inconceivable. . . .

Finally, it may be noted that Huygens nowhere discusses phenomena of color or of diffraction. This is interesting, since Newton, in an attempt

[2] Bartholin, *Experimenta crystalli Islandici disdiaclastici quibus mira et insolita refractio delegitur* (Copenhagen, 1670).

[3] D. N. Mallik, *Optical theories* (Cambridge Univ. Press, 1917). The law that determines the intensity at each point of the secondary wave was not determined until the middle of the nineteenth century, when it was announced in 1849 by Stokes: "On the dynamical theory of diffraction," Cambridge Phil. Trans. **9**, 1–62 (1856).

[4] Huygens nowhere claims the wave theory to be his own invention. Like the corpuscular theory of light, the wave theory has roots that go back beyond the seventeenth century.

to explain color and diffraction phenomena was led to postulate waves while advocating the corpuscular theory of light.

Newton's first important scientific work was done in the field of optics. In his first publication,[5] a paper containing an account of dispersion and the composition of white light, he showed (1) that by means of a prism white light could be decomposed into light of different colors and different refrangibilities; (2) that there was a one-to-one correspondence between the colors and the degrees of refrangibility; (3) that because of this correspondence, if light of given color and refrangibility were separated by means of a slit from the rest of the light issuing from the prism, there could be no further decomposition; and (4) that by means of a prism oriented in a diametrically opposed position to the original one, the decomposed light—of many colors and refrangibilities—could be recomposed into white light. The discovery of dispersion convinced Newton that the possibilities of the refracting telescope were very limited and turned his interest in the direction of the reflector. He stated dogmatically that dispersion permitted no correction, thus failing to realize that it might be possible to design an achromatic lens system as a means of reducing this effect.

At the time of the publication of Newton's paper, there was a tremendous amount of confusion about the nature of colors. Because the simple results of Newton's experiments ran contrary to all of the speculations of the time, the paper aroused a storm of hostile criticism. The two who objected most strongly and most violently to Newton's ideas based their objections not so much on his conclusions as on his suppositions—explicit as well as implicit. These two were Ignatus Gaston Pardies (1636–72) and Robert Hooke (1635–1703), both proponents of the wave theory of light. Hooke's attacks were particularly vicious and their effect was to give Newton such a horror of controversy that he afterwards cared very little to have his works published. This explains his seeming lack of interest with regard to the publication of the *Principia mathematica*. It may be noted, too, that Newton refused to allow his *Opticks*[6] to be published until 1704, just one year after the death of Hooke, although the manuscript had been ready for many years.

Among other things, Hooke accused Newton of arguing the "corporeity" of light. To this Newton made reply:

> 'Tis true, that from my Theory I argue the Corporeity of Light; but I do it without any absolute positiveness . . . and make it at most but a very plausible *consequence* of the Doctrine, and not a fundamental *Supposition*. . . . I knew, that the *Properties*, which I declar'd of *Light*, were in some measure capable of being explicated not only by that, but by many other Mechanical *Hypotheses*. And therefore I chose to decline them all, and to speak of *Light* in *general* terms, considering it abstractly, as something or other propagated every way in streight lines from luminous bodies, without determining, what that thing is. . . .

He then goes on to show that neither the phenomenon of dispersion, nor his own explanation of the composition of white light, is inconsistent with a wave theory of light, pointing out in conclusion, that

> [if] the Vibrations which make *Blew* and *Violet*, are supposed shorter than those which make *Red* and *Yellow*, they may be reflected at a less thickness of the Plate: Which is sufficient to explicate all the ordinary *phaenomena* of those Plates or Bubles, and also of all natural bodies whose parts are like so many fragments of such Plates.

The last reference is to the writings of Hooke on the colors in soap bubbles and in "Muscovy" glass. Thus, it is clear that what Newton wished to demonstrate was that his own findings were so perfectly compatible with the wave theory of light that there was no need for his "objector" to "apprehend a divorce from it." But, in his own turn, Newton raises an objection to the wave theory. He asks how[7]

> the *Waves* or Vibrations of any Fluid, can, like the Rays of Light, be propagated in *Streight* lines, without a continual and very extravagant spreading and bending every way into the quiescent Medium . . . ?

[5] "New theory about light and colors," Phil. Trans. **6**, 3075–3087 (1672). See also Sarton, "The discovery of the dispersion of light and the nature of color," Isis **14**, 326–341 (1930), containing a facsimile reproduction of Newton's paper. Newton's paper appears in Magie, ref. 1.

[6] *Opticks* (ed. 1, London 1704; later editions, 1717, 1721, 1730). The fourth edition may be conveniently obtained in a reprint edited by E. T. Whittaker, with an introduction by A. Einstein (Bell, 1931). Extracts may be found in Preston, *Theory of light*, supplement to chap. V.

[7] Newton, "Answer to some considerations upon his doctrine of light and colors," Phil. Trans. **7**, 5084–5103 (1672).

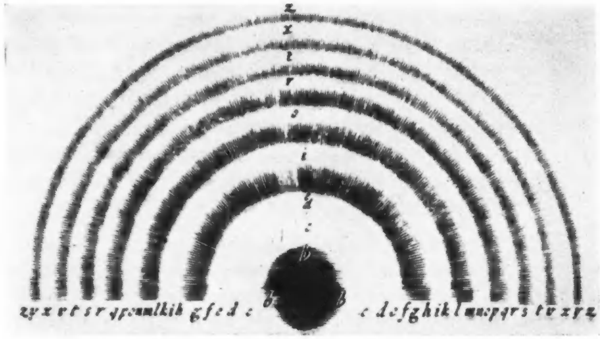
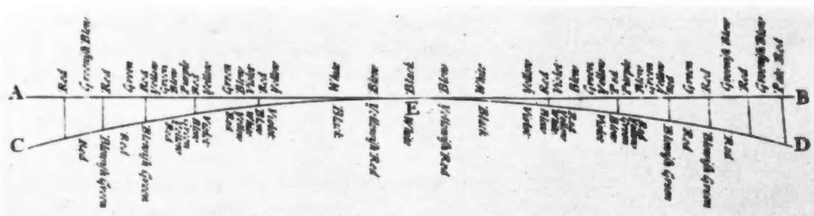


Plate I of Book II of Newton's *Opticks* (ed. 1). "Their form, when the Glasses were most compress'd so as to make the black Spot appear in the center, is delineated in the second Figure; where *a*, *b*, *c*, *d* : *f*, *g*, *h*, *i*, *k* : *l*, *m*, *n*, *o*, *p* : *q*, *r* : *s*, *t* : *v*, *x* : *y*, *z*, denote the Colours reckon'd in order from the center, black, blue, white, yellow, red : violet, blue, green, yellow, red : purple, blue, green, yellow, red : green, red : greenish blue, red : greenish blue, pale red : greenish, blue, reddish white."



Herein is embodied one of Newton's chief objections to the wave theory of light. Never answered for him in his whole lifetime, this objection appears many times in the *Opticks*, but is stated most clearly in Query 28 of Book III. In this query, he states too (and correctly) that the only attempt to account for "the unusual Refraction of Island Crystal" by means of the wave theory was that of Huygens in his *Traité*. But in that explanation, there is, for Newton, a major flaw:

> For Pressions or Motions, propagated from a shining Body through a uniform Medium, must be on all sides alike; whereas by those Experiments [those described by Huygens] it appears, that the Rays of Light have different Properties in their different sides.

This is certainly valid criticism; there could be no explanation of polarization by means of a theory that considered light to consist of a series of longitudinal pulses. Polarization was given no adequate explanation until the nineteenth century, when light was finally conceived of as being a transverse vibration.

Had Newton but realized how very small the wave-lengths might be, if light were composed of waves, he might very well have been able to cross the hurdle of rectilinear propagation. For Newton was quite familiar with the phenomena of diffraction. Book II, by far the longest of the three parts of the *Opticks*, is concerned almost entirely with diffraction (which Newton called "inflection") and what we know today are varieties of interference phenomena. Let us see how Newton obtained his rings (Book II, Part I, Obs. 4); he says

> I took two Object-glasses, the one a Plano-convex for a fourteen Foot Telescope, and the other a large double Convex for one of about fifty Foot; and upon this, laying the other with its plane side downwards, I pressed them slowly together, to make the Colours successively emerge in the middle of the Circles. . . .

Newton made many careful and varied experiments and measured the rings under different conditions. He discovered the numerical relations between their diameters and the difference between the rings when viewed under white light and monochromatic light.

Newton was hard put, however, to explain how the same kind of rays of light striking a thin plate would be alternately reflected and refracted (or transmitted) for a long and regular succession. As a means of explanation he offered the following (*Opticks*, Book II, Prop. 12):

> Every Ray of Light in its passage through any refracting Surface is put into a certain transient

> Constitution or State, which in the progress of the Ray returns at equal Intervals, and disposes the Ray at every return to be easily transmitted through the next refracting Surface, and between the returns to be easily reflected by it.

He defined these dispositions of the ray to be reflected as "Fits of easy Reflexion" and those dispositions of the ray to refraction as "Fits of easy Transmission." He further assumed the length of the interval between any two consecutive fits of easy transmission, or of easy reflection, to be a simple function of the color. He supposed that this length would be greatest for violet and least for red, and that it would vary monotonically through the range of colors between these two. It may thus be seen, as pointed out by E. T. Whittaker,[8] that "Newton's length of fit corresponds in some measure to the quantity which in the undulatory theory is called the wave-length." But the theory of fits was not sufficient to explain all of the experimental data, and so Newton was led into more and more cumbersome and complicated assumptions.

Although Newton clearly advocated the corpuscular theory, at the same time he recognized that light was a periodic phenomenon. The problem of accounting for periodicity by means of a corpuscular theory is almost insuperable, and hence Newton was finally forced to postulate waves as a sort of concomitant of the corpuscles in the ether, although he never could accept the idea that these waves constituted the light itself. He was fortunate in finding an example in nature that presented a situation analogous to the one in which he was interested. In Query 17, Book III, of the *Opticks* he explains how a stone (the analog of a corpuscle) can be thrown into the water (the analog of the ether inside, say, a prism) and can thereby excite waves that will continue to spread in the water long after the passage of the stone. He then asks:

> And in like manner, when a Ray of Light falls upon the Surface of any pellucid Body, and is there refracted or reflected, may not Waves or Vibrations, or Tremors, be thereby excited in the refracting or reflecting Medium at the point of incidence . . . ? And do they not overtake the Rays of Light, and by overtaking them successively, do they not put them into the Fits of easy Reflexion and easy Transmission described above?

Following this, Newton repeats the idea, discussed before apropos of his reply to Hooke, that color can be connected with these concomitant waves, saying:

> Do not several sorts of Rays make Vibrations of several Bignesses, which according to their bignesses excite Sensations of several Colours, much after the manner that the Vibrations of the Air, according to their several bignesses excite Sensations of several Sounds . . . ?

He adds that the most refrangible rays excite the shortest vibrations to produce violet, while the least refrangible rays excite the longest vibrations to produce red.

There were few writers on the wave theory of light in the eighteenth century, the most important being the mathematician, Leonhard Euler (1707–1783). Euler built up a theory of colors based on what he called "induced vibrations" and used it in an attempt to explain Newton's rings. He added nothing of material value to the problem, however, and seems merely to have substituted one kind of mechanistic device for another.

The first significant advance was made by Thomas Young who, as we remarked at the beginning of this article, invented the principle of interference and used it to give a satisfactory explanation of the rings. He made his discovery in 1801 and published it the following year.[9]

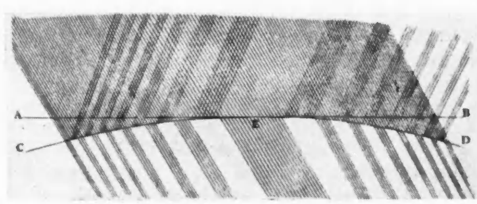


Plate I of Book II of Newton's *Opticks* (ed. 1). Newton's schematic representation of the "fits of easy reflexion" and of "easy transmission."

[8] Whittaker, *A history of the theories of aether and electricity* (Longmans, Green, 1910), p. 21.

[9] "On the theory of light and colours," a Bakerian lecture, Phil. Trans. **92**, 12–48 (1802). The theory of interference is also to be found in his *A course of lectures on natural philosophy and the mechanical arts* (London, 1807) and in its predecessor, *A syllabus of a course of lectures on natural and experimental philosophy* (London, 1802).

Young had written several earlier papers in which he had espoused the cause of the wave theory, but it was not until the formulation of the principle of interference that he was able materially to advance the state of knowledge thereby. These papers, which are of great interest, are packed with quotations from Newton in order to show that the author was extending and clarifying the work of the author of the *Principia mathematica*. But if Young thought that by this means he would avoid the antagonism of those who would think he was casting aspersions on the name of the great man, he was sadly mistaken.

No sooner had his paper appeared than Young became subject to one of the most violent and undeserved attacks in the history of science since the seventeenth century. The attack appeared in *The Edinburgh Review* and was written by Henry Brougham, afterwards Lord Chancellor of England. It was published anonymously and its venom is difficult to surpass, as the following samples may indicate: "It is difficult to deal with an author whose mind is filled with a medium of so fickle and vibratory a nature"; "We now dismiss . . . the feeble lucubrations of this author, in which we have searched without success for some traces of learning, acuteness, and ingenuity, that might compensate his evident deficiency in the powers of solid thinking . . . ." Young replied in a pamphlet of which, according to his biographer Peacock, but a single copy was sold. Brougham carried the day and, in England at least, the budding undulatory theory received a severe setback from which it was not to recover until about twenty years later with the recognition of the work of Fresnel by the Royal Society, of which Young was secretary.

When Young first began to develop the theory of interference, he came upon what seemed to be a major flaw. For, although he was able to explain the colors of thin plates by the interference of the parts of the beam of light (one part reflected at the first surface of the plate and the other reflected at the second), he was puzzled by the fact that the central spot in Newton's rings was black rather than white. Since the thickness of the air is zero at the center, he first thought that the interfering beams should be similar, thus giving an effect of white, not black. But he finally decided, considering the analogy with the impact of elastic bodies, that light undergoing reflection at the surface of a denser medium has its phase retarded by half an undulation. Thus the beams would interfere destructively at the center of the rings (provided the lenses be in air), and on this basis he predicted that if the lamina between the two lenses was intermediate in refractive power to the two lens mediums, the order of the rings would be reversed and the center spot would be white. An experiment in which the air was replaced by essence of sassafras, and in which one lens was made of crown, and the other of flint glass, confirmed this prediction. Another of his demonstrations of interference was the famous experiment in which light from a single source is divided by means of two adjacent pinholes into two identical beams which are then allowed to interfere.

Young was led to a very interesting result by a reinterpretation of Newton's observation that rings produced in oil or water, rather than air, follow the ordinary laws except that they are greatly contracted in diameter. Young interpreted this to indicate that the larger the refractive index of the medium, the shorter would be the wave-length of the light, hence, the lower the speed. Newton, and all of the advocates of the corpuscular theory from Descartes to the nineteenth century, had been forced to conclude that the larger the refractive index of the medium, the higher would be the speed. Young's conclusion, the opposite of this, had been previously advanced by Fermat in opposition to Descartes, and had been seconded by Huygens and Roemer. This conclusion was in agreement with the calculations of Fresnel who, like Young, claimed it to be a necessary consequence of the wave theory of light. Thus was the stage set for the great *experimentum crucis* of Foucault, who measured the speed of light in air and in water to establish by direct experiment that the prediction of the wave theory was correct.[10]

Young, in the pamphlet written in reply to

[10] Foucault's results were published in the Comptes rendus **30**, 551–560 (1850). For a comprehensive history of the ideas concerning the velocity of light see I B. Cohen, "The first determination of the velocity of light," Isis (in press).

Brougham,[11] states how he was led to the discovery of the law of interference:

> It was in May 1801 that I discovered, by reflection on the beautiful experiments of Newton, a law which appears to me to account for a greater variety of interesting phenomena than any other optical principle that has yet been made known. I shall endeavor to explain this law by a comparison.

The comparative example of which he makes use is that of equal water waves on a lake, moving with equal speed. If they arrive at a certain channel in phase their effect is doubled, but if they arrive exactly out of phase their effects are mutually canceled. He continues:

> I maintain that similar effects take place whenever two portions of light are thus mixed; and this I call the general law of the interference of light.

After showing in some detail how this law agrees with, and tends to clarify the understanding of, the phenomena recorded in the *Opticks*, he concludes that

> there was nothing that could have led to it [the law] in any author with whom I am acquainted, except some imperfect hints . . . in the works of the great Dr. Robert Hooke . . . and except the Newtonian explanation of the tides in the Port of Batsha.

In a later article,[12] Young showed the similarity of the interference of light and Newton's general theory of the tides (and also of the explanation of musical "beats"):

> The spring and neap tides, derived from the combination of the simple solar and lunar tides, afford a magnificent example of the interference of two immense waves with each other: the spring tide being the joint result of the combination when they coincide in time and place, and the neap when they succeed each other at the distance of half an interval.

Let us examine the careful way in which Newton himself had explained the tides at Batsha. This is certainly the most interesting aspect of our story. For Newton's explanation, although plausible, is incorrect; yet, in this explanation, he worked out all the details of the theory of interference which he needed so badly in order to explain the phenomena described by him in the *Opticks*.

[11] Reprinted in *Miscellaneous works of Thomas Young*, ed. by Peacock (John Murray, 1885), vol. 1.

[12] "Chromatics," written in 1817 for the supplement to the *Encyclopaedia Brittanica*.

The port of Batsha in Indo-China is situated in the northwest part of the Gulf of Tongking, at the mouth of the Domea (or principal) branch of the Tongking River, in about latitude 20° 50′ N. The first account of the Batsha tides was written by a shipmaster, Francis Davenport, and communicated to the Royal Society of London with a very imperfect explanation by Edmund Halley.[13] These tides do not seem so strange to us today as they must have seemed to the scientists of the seventeenth century. For there was then little data concerning tides in different parts of the world; and, in addition, the theory of the tides did not exist on anything approaching a scientific basis before Newton's *Principia mathematica*,[14] and the law of universal attraction. Indeed, Galileo had ridiculed the very notion that the motion of the moon might affect the tides of the ocean, believing that such an idea smacked of pure occultism.

At Batsha, there is usually but one flood and one ebb tide every twenty-four hours rather than the customary two of each. When the moon is near the equator, twice in every lunar month, there is about a two-day period in which there appears to be little or no tide. For approximately the first seven days after this tideless period, the tides increase gradually until they attain a maximum; then they fall off gradually for about seven days when they reach another stationary period of two days.

Before giving an account of Newton's explanation of this phenomenon, a few words about the accepted current explanation are in order. The tide-producing forces of the sun and moon fall into three general classes—the diurnal forces, those having a period of approximately 24 hr; the semi-diurnal forces, those having a period of approximately 12 hr; and those of period of half a month or more. Although these forces are distributed over the earth in a regular way varying with the latitude, the response to them of any particular sea depends upon its own geographic features.

Each body of water has a natural period of oscillation which is a function of its length and depth, and thus it will respond best to that disturbing force which has a period most closely approximating its own natural period. Thus the Atlantic Ocean responds best to the semi-diurnal forces, and, as a result, we on the Atlantic coast are accustomed to two ebb and two flood tides daily. The Gulf of Tongking,

[13] Phil. Trans. **14**, 677–688 (1684).

[14] Edition 1, London, 1687, bearing Pepy's authorization as of July 5, 1686.

on the other hand, responds almost perfectly to the diurnal forces, and, as a result, there is usually but one flood and one ebb tide a day. (To a somewhat less degree, the same conditions obtain in the Gulf of Mexico; at Pensacola, Florida, for example, there is usually but the one flood and one ebb tide daily.) As the amplitudes of the semi-diurnal constituents of the tide in the Gulf of Tongking are negligible, at the period when the moon is on the equator (twice monthly) the water remains stationary or tideless for about two days, since at that time the diurnal constituents are ineffective. When the moon is either north or south of the equator, as the case may be, these diurnal constituents become more and more effective as the moon becomes farther and farther north or south until the time that the moon begins its return to the equator. This accounts for the variation in the degree of the tides between the tideless periods.[15]

A pioneer in tide theory, Newton had no understanding of the tide process as just outlined. But the explanation he offered of the unusual tide at Batsha is sound enough within the framework that he describes in the course of his discussion. It is of much interest in view of the main subject under discussion here. Proposition xxiv of Book iii ("The System of the World") of the *Principia mathematica*[16] states "That the flux and reflux of the sea arises from the actions of the sun and the moon." This is the section referred to by Young in his article on chromatics mentioned earlier. Newton concludes this section of his book with:

> Further, it may happen that the tide may be propagated from the ocean through different channels towards the same port, and may pass quicker through some channels than through others; in which case the same tide, divided into two or more succeeding one another, may compound new motions of different kinds. Let us suppose two equal tides flowing towards the same port from different places, one preceding the other by six hours; and suppose the first tide to happen at the third hour of the approach of the moon to the meridian of the port. If the moon at the time of the approach to the meridian was in the equator, every six hours alternately there would arise equal floods, which, meeting with as many equal ebbs, would so balance each other that for that day the water would stagnate and be quiet.

He then proceeds to describe how the position of the moon with regard to the equator can cause other combinations, due to these various channels, and thus accounts for all the data of the tides at Batsha. If we remember that the tide can be considered as a wave whose crest corresponds to the flood, and whose trough corresponds to the ebb, we see immediately that Newton's explanation consists of all of the varieties of interference from destructive to corroborative.

After concluding the explanation, which he insists is only a tentative one to be checked and verified, he adds in true scientific spirit:

> There are two inlets to this port and the neighboring channels, one from the seas of *China*, between the continent and the island of *Leuconia;* the other from the *Indian* sea, between the continent and the island of *Borneo*. But whether there be really two tides propagated through the said channels . . . which . . . by being compounded together, produce these motions; or whether there be any other circumstances in the state of those seas, I leave to be determined by observations on the neighboring shores.

Thus we see that Newton worked out the theory of interference a hundred years before Young, although the principle of interference does not apply to the instance that he used. He never thought of applying it to the phenomena of optics where it would have been most useful. It had to be rediscovered and applied by Young in order to account for the very phenomena that Newton had investigated and described in such detail, but for which he could give no adequate explanation. With the rediscovery of this principle by Young, the wave theory of light was reborn, and in the hands of Fresnel, the principle permitted an explanation of polarization. Thus it became the chief weapon with which the nineteenth century was able to break the eighteenth-century reign of the corpuscular theory of light.

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[15] For the information about the tides, I am indebted to J. H. Hawley, Acting Director of the U. S. Coast and Geodetic Survey. For a thorough account of the subject, consult H. A. Marmer, *The tide* (Harpers, 1926). For a simple outline of the subject, consult P. C. Whitney, "Some elementary facts about the tide," J. Geography **34**, 102–108 (1935).

[16] The *Principia mathematica* may be conveniently obtained in an English translation by Andrew Motte (1729) of the fourth edition, revised and modernized by Florian Cajori (Univ. of California Press, 1934). This edition contains a useful historical and explanatory appendix of about 100 pages by Cajori.

Research and the College Teacher

Thomas H. Osgood
Department of Physics, The University of Toledo, Toledo, Ohio

MANY of the troubles which beset a teacher of physics originate in the fact that there are too many things for him to do. The trend of the times is to develop a close and informal relationship between student and teacher, a desirable but time-consuming aim. At the same time, a teacher has a pride in his institution which encourages him to do something to add to its prestige by maintaining its reputation for scholarly work. This something usually takes the form of research which can be published in reputable journals, but for a variety of reasons it is becoming more and more difficult to carry on research with only the traditional assets of wax and string. In this paper I have tried to analyze the situation of the college teacher in his relation to current research. Since I am not aware of possessing any exceptional qualifications for the task, my effort is made rather as a spokesman for the readers of this Journal than as one who has new ideas to propound. It may be, however, that the opinions set forth below are not truly representative of the American Association of Physics Teachers. In that case, there will be something to argue about.

For several years now I have been writing about research without actually taking any part in digging the material out at the face, as it were. Yet I do not feel that any stigma can be attached to this dealing in secondhand goods, for they are of the very highest quality—their pedigree can be traced through the pages of *The Physical Review*, the *Proceedings of the Royal Society*, *Nature* and such journals, back to the most reliable research laboratories in many countries. Like most of you, my chief occupation has been the teaching of physics; but when I consider the question of the teacher's relation to current research, I do not feel as though I were looking at the majestic heights of research with a telescope from a vast distance, even though I have taken little part in it. For if we are to admit that research is valuable at all, then teaching and research must be closely coupled. In the long run they must necessarily play complementary roles, in much the same way as a distributor and a manufacturer cooperate in bringing a new product before the consumer.

From a theoretical point of view it would be desirable to define the meaning of research, but from a practical aspect it is easier to leave it unrestricted, because it has different meanings for different individuals, and its reaction upon different individuals is never the same. Nor are the motives which urge a man toward research the same as those which encourage his friends. The fundamental drive probably comes from a desire that is found in all keen minds to leave something worth while behind them, something without which the world would have been poorer. Man's faith in the permanence of material things, of nations and of wealth, and of the possessions which he may acquire during his lifetime is fast diminishing, for he has seen changes of incredible magnitude in such things take place within the last decade. The keen mind, sensing the joy of accomplishment, and actuated perhaps by a praiseworthy selfishness, sees the most lasting memorials to be those which bring to light new ideas that will add to the sum total of our knowledge.

Perhaps I should elaborate a little on the answer to the question, "Why does a teacher need to know what is going on in research?" A blunt reply might be given by saying that only thus can new life be put into teaching, but such an answer fails to bring out the essential points of the close relationship between student and teacher. It is hardly necessary to stress the respect which a teacher can command from a group of students; he is their guide in many ways, and their model too. This respect depends to a large extent on how well the teacher is able to interpret to his students this world in which we live. Our newspapers pretend to give us complete news service which includes a good deal of ballyhoo about modern scientific developments. Students do read newspapers, especially if campus publications appear only infrequently. They are puzzled, for they have no years of

experience on which to draw, and few newspaper articles are in the least analytic in their presentation of facts. They often stress the less important things because they are merely bigger or more showy than others. For example, about a year ago the press carried feature pictures of the new magnet of the great cyclotron which is being built at the University of California, rigged up for certain spectroscopic experiments. All the emphasis in those pictures and stories was on the size of the magnet, and it was difficult to find out what was really being done with it. It was not surprising that the news accounts puzzled the students, for they puzzled their teachers too; but they served a worthy purpose in stimulating the curiosity of both.

However, it does not always happen that a student's creative curiosity is aroused by an account of difficult experiments. On one occasion, after discoursing, as I thought, very lucidly on precision experiments for determining the speed of light, I was rather taken aback by the question, "But isn't there a machine for doing all that?" In this one query you find the expression of the attitude of a goodly proportion of students. They are the button-pushers. They pull a single formula out of a textbook, mix up the necessary ingredients and expect a correct answer to come out without the exercise of anything but routine mental processes. And if the machine fails to start at the push of a button, or if the problem fails to give the answer found at the back of the book, they want to call in a service man, or consult their professor. As teachers, we try to stimulate creative thinking among our students, but sometimes it is difficult even to get to first base, if I may put it that way, by convincing students that there are no regular service men for creative activities.

I need hardly dwell on the obvious fact that a teacher cannot hope to present material to a class in a persuasive manner unless it is evident that the presentation merely scratches the surface of his own knowledge. I have clear but rather painful recollections of my first halting efforts at instruction, though they seemed rather satisfactory to me at the time. Such stumblings can hardly be avoided, for one must begin sometime. But they serve to remind me of the responsibility that rests with the senior members of the American Association of Physics Teachers, the responsibility of guiding the teaching, as well as the studies, of their young colleagues.

I am still trying to answer the question, "Why does a teacher need to know what is going on in research?" Most campuses cherish the apocryphal legend of the professor who gives the same lectures now as were delivered to him "at dear old Pocahontas in 1903." But no such legends can surround a physics department. If it is healthy it is always in a state of flux, and this is especially true of a laboratory. Here a knowledge of instrument development is of prime importance, but only in advanced classes. For what may seem a most elegant method of measurement to us may confuse a beginner. In measuring the stretch of a wire, the complexity of an optical lever may divert a student's attention from the main purpose of the experiment. New devices should, of course, be used but with discretion. A vacuum-tube voltmeter may seem incomprehensible, but even a child will accept with perfect equanimity the production of sound by a radio; synchronous motors may be a closed book to a freshman, but he will happily measure time intervals in the laboratory with an electric clock and tapping key.

These, then, are some of the reasons why a teacher must be interested in research. They are the exterior reasons, if I may borrow a term from ballistics; an important interior reason, the possibility of professional advancement, will be considered a little later.

It would be well to inquire now what parts of research are most important from a teacher's point of view, and here we must be guided by the type of students we confront. It is probably no exaggeration to say that 90 percent of students of physics are in elementary or first-year classes, and that teachers spend 70 percent of their teaching time with them. For this numerical majority, matters of principle are usually best driven home by illustrations taken from industrial research, whose products are already finding their way into students' homes. How much better, for example, to refer to the effect of variations of temperature on the viscosity of automobile lubricants or of tooth paste, or to the thermal conductivity of the walls of a house or of ice cream, rather than to refer to the difficulties

in the oil-drop experiment, or to the flow of heat along an isolated bar of metal, academically and artificially swathed in cotton!

Nevertheless, although only 10 percent of our students study more than the elements of physics, we must not jump to the conclusion that academic research can be pushed into the background. From this 10 percent come those who are destined to carry on our torch. They must be trained well, for they are more deserving than their numerical strength suggests; and they know enough of the subject to be interested in the important experiments of pure research, with which the teacher must therefore be familiar. And thus we come to the conclusion that a good teacher should be acquainted with practically all lines of research; obviously a distressing conclusion, for it is well-nigh impossible of accomplishment. But it is not our habit to look squarely at a difficulty and then turn our backs upon it. At least we must ask what we can do about it.

Teachers do not have the time, and some have no libraries, in which to read all the papers that might help them. They must study, to a great extent, from abstracts or reviews. Abstracts we have in plenty, but they should be couched in less technical language than the papers they represent. You might be interested to glance through *Science Abstracts A* and compare the items written by professional abstractors, and those labeled "Author." An abstract, or a review, should be written for someone who knows very little about the subject; the man who is a specialist in the field will read the paper anyway. I was interested in what Sir William Bragg had to say on this topic a year or two ago:

> Men of science cannot be given the direction of the affairs in which their discoveries play a part, even if they had the inclination to do so, just because they made the discoveries, but they are in duty bound to see that the knowledge is rightly stated so that it may be used properly. Summaries should not be just a brief digest, but should be different from the paper itself, addressed to a much wider circle of readers, including experts and others who should receive the major share of attention.

He made some further remarks on the possibility of restricting the quantity of published matter, arguing that there must always be a place for material that is really new; but if there is a steady output of observation, extension, confirmation and illustration, with many figures and bulky tables, then it is time for a reconsideration of the contents of the journals. It appears, therefore, that it would be well to aim at less frequent but well-coordinated reports in the research journals.

From abstracts and reviews it is only a few steps to the process of popularization, but they are difficult steps. Yet I am convinced that teachers could do much more than they do in the way of disseminating sound scientific knowledge beyond the boundaries of their classrooms, and I feel that such activities in the promotion of science should be evaluated as research on the part of the teacher. If your experience has been anything like mine, there come to you as many invitations as you can reasonably accept to speak before clubs and other organizations. A teacher has an advantage, for he is by profession a speaker, and there are many kinds of research which lend themselves well to dramatic but simple presentation. But he must not expect to interest everybody, and should rate his effort a success if he is asked even one intelligent question.

We all derive a great deal of inward satisfaction from doing a job well, though in the long run that is hardly enough to keep us enthusiastic and spur us on to greater efforts. We hope for occasional material rewards, in the shape of promotion or transfer to what we think will be a more congenial atmosphere. Except in the case of geniuses, there is now little movement of teachers from one institution to another after the age of, say, 35. Up to that age, teachers are not usually chosen for their teaching ability, but for their prowess in research of the Ph.D. variety. Some institutions choose such men for the prestige they bring, and successfully prevent further development of that prestige by having no adequate facilities for research, through no fault of their own. There are cases on record, of course, in which large institutions have added men to their faculties merely on the grounds of their good teaching. But there are others in which an institution has contemplated hiring such a teacher of repute, only to change its mind on discovering that he is not also a prolific publisher of papers. There is something seriously wrong here, either with the appraisal of what

constitutes good teaching, or with the conception of what kind of creative work may reasonably be expected of a full-time teacher. I find mutterings on the subject even in some of the undergraduate dailies. Yale—and I am speaking of undergraduate opinion—recognizes that a university has a dual function, the dissemination of knowledge and the maintenance of high standards of scholarship, but sees that in practice these are sometimes mutually contradictory. The solution of the difficulty, it is suggested, is to separate the two functions; a suggestion which seems to have arisen from the confidence of inexperience. It is almost too much to expect an expression of the same opinion from Princeton! Its undergraduates say that it is not surprising to find lecturers and preceptors criticized, that a man who does not put his instructional duties first cannot hope to be a good teacher, that the fault lies only partly with the professor, who cannot be blamed for realizing on which side his bread is buttered. It may be that these two groups of undergraduates did not know how a professor's time is spent. Figures which were quoted to me as representative of a large institution, well known for its research, show that faculty members spend 50 to 60 percent of their time in work connected with teaching, and only 14 percent in research.

Although several technics are available for the appraisal of teaching, I am not aware that any of them is wholly satisfactory. In spite of this, we ought to do something to insure that young physicists destined for college positions have supervised training in classroom work. Far be it from me to recommend that courses called "Psychology and sociology of physics" be offered in our graduate schools in order that students may be prepared to fulfil their functions as instructors. Yet there ought to be some token as definite as a thesis which is indicative of their accomplishments as teachers. It will then turn out that those graduate students who have good teaching qualifications will find positions most readily; and that is because most vacancies are for men who are teachers in the first instance.

Not that I am belittling research; teachers must do something creative to keep themselves alive, but we have got into the rut of regarding formal research as the only creative thing a teacher ought to do. That this is far from true deserves much greater emphasis that I can give here.

Modern research in experimental physics at the universities is growing more and more to be a cooperative enterprise. The scale on which research is undertaken and the organization which it demands are reminiscent of the best business methods. Results are turned out with amazing speed. In a small institution a man is usually his own mechanic, glass blower, handy man, purchasing agent, errand boy, etc. He cannot make any such speed. If this present trend continues, small institutions are going to be pushed out of the picture as far as up-to-the-minute research is concerned. In them, a teacher should think seriously before undertaking any such research, for fear of discouraging delay. Of course, there are some men who *must* do such research; but there are far more, to be perfectly honest, who drive themselves to it for various reasons. But if they choose wisely, they can find many suitable problems in classical physics requiring very little more apparatus than an elementary laboratory provides; or they can work on problems of a subsidiary nature which have been sidetracked in the swift rush toward great discoveries. Moreover, such problems will tax their ingenuity as much as larger ones. And they must remember that they can do a good job of teaching. There is no reason why small colleges should not turn out even better physics majors than some well-known centers. Small colleges can thus keep to the forefront as fine places in which to receive a liberal education.

Nearly every teacher dreams of writing a perfect textbook, though the dream often turns into a nightmare when he begins to wonder what material should be included. The point which interests us at the moment is to what extent modern research should influence the content of an elementary textbook. Most of us belong to one of two camps. Either we are extremists, anxious to include a great deal, or we are middle-of-the-roaders, willing to admit the highlights of recent research only when time, after a decent interval, has mellowed and simplified their interpretation. Neither attitude can be right, neither wrong. But the extremists run the risk of misinterpretation, for elementary students are noto-

riously prone to take things a trifle too literally, and there is no space in an introductory treatment to clarify the meaning of all the neat phrases we use. I have vivid recollections of a lecture given several years ago by E. A. Milne, now Professor of Mathematical Physics at Oxford, before the Cambridge Philosophical Society. He was to communicate to the society the nature of certain calculations he had been making concerning stellar atmospheres. Usually such lecturers had audiences of about 25, but on this occasion a large room was filled to overflowing by visitors and undergraduates of both sexes. Their disappointment and boredom as Professor Milne covered the blackboards with thermodynamic formulas were, I hope, not obvious to the speaker. And it was not until afterwards that it was realized why so large an audience had come. The notice advertising the meeting would have done justice to a professional humorist. It said that Professor Milne would speak on "The Mean Life of an Excited Calcium Atom."

But to return to our subject. Occasionally what a journalist would call a *natural* turns up. A generator of the Van de Graaff type is a good example; it is simple in principle and offers so direct an illustration of the definition of potential difference in terms of work per unit charge that it should find a place in every account of electrostatics. However, I believe that debate as to what should or should not be included is a needless one, unless the textbook is designed for self-study. We are inclined to fall into the habit of thinking of the textbook as being the teacher, and with this in mind you will derive some amusement from reading an article in the December *Atlantic Monthly* on "The Reform of the Schools." Emphatically the textbook is not the teacher. Any textbook recommended to a class must be pruned in some places and elaborated in others; but the pruning and elaboration should, and will, vary from year to year, or the subject matter will degenerate into a dull routine for both student and instructor.

What I have given here makes rather a patchwork quilt. I have touched on various aspects of research as it affects the teacher. But I have reached no satisfying conclusion, nor suggested any definite attitude which we teachers should adopt toward research. Obviously, we cannot ignore research and devote all our time to teaching; yet teaching is a whole-time job. Nor must we let young physicists be trained to look on research as the be-all and the end-all here. Such worship of research would put teaching on the same plane as surgery was a century or two ago—a sideline of the barber's trade. Nor would it please me to see the teaching of physics reduced to the series of rules and attitudes that characterize the training of school teachers today. One cannot reasonably say, once a teacher, always a teacher. A good teacher of science is essentially an individual—for teaching is a meeting of personalities—an individual who can graft his own methods, unconscious methods if you like, on the broad outline recommended by his predecessors. Nor do I believe that the details of teaching yet constitute a field of research in the same sense as the investigation of a scientific problem does. We shall always have research specialists; but they are frequently poor interpreters. And for everyone who has time to do research there are a hundred who have not, or do not know how, but who are interested in the game. Here, to my mind, lies the great opportunity for the teacher. He knows the attitude of the people who are interested in hearing about research, and he usually has the solid background necessary for the presentation of new results in an attractive way. No piece of research is ever perfect when it is first published. It has to be argued over, discussed from all sides, looked at from new points of view which will illuminate and clarify. If teachers will pursue this course, that of interpreting research, as an alternative to suffering the disappointment of research that does not "work out," they will find themselves better and keener students, not in the position of camp followers, but in the position of liaison officers between the centers of research and the general body of citizens who are, in the last analysis, the group on whose interest the harmonious continuation of scientific research depends.

Resolving Power and the Theory of the Pinhole Camera

LOUIS A. TURNER
Princeton University, Princeton, New Jersey

THE pinhole camera is of great value in the teaching of photography. Many of the essential points concerning perspective, wide-angle lenses, etc., can be demonstrated with it quite as satisfactorily as with elaborate, expensive equipment. Further, for those who give courses in which stress is laid on all the physics involved as well as on the purely photographic aspect, the discussion of the pinhole camera leads naturally into the consideration of diffraction, resolving power and best definition. The treatments of the pinhole camera in the textbooks with which the author is familiar are unsatisfactory from this latter point of view. They are not sufficiently explicit concerning the variations of the diffraction pattern with changing size of the pinhole, and the way in which this affects the quality of the picture. Various formulas are given for the optimum size of the pinhole which agree only as to order of magnitude. A thoughtful student naturally is puzzled by this. Either there is a theory leading to one correct result and explainable clearly in principle, no matter how complicated it is in mathematical detail, or else there is an unavoidable inexactness in the whole matter, the character of which should be made clear. The latter seems to be the actual situation. The purpose of the present paper is to give a fairly detailed treatment which can be adapted by teachers to the degree of preparation of their students.

The results of the treatment are as follows:

(1) The optimum diameter a of the pinhole is given by the expression

$$a=2[K\lambda vu/(u+v)]^{\frac{1}{2}}, \qquad (1)$$

where λ is the wave-length of the light, u is the distance from object to pinhole, v is the distance from plate to pinhole and K is a numerical factor of the order of unity.

(2) The value of the numerical factor K can be determined theoretically only by postulating some criterion for best definition. There is no such criterion which is obviously the correct one. This is the root of the uncertainty in the whole matter.

(3) Maximum resolving power as determined for spectrographs and other optical instruments leads to a value of 1.2 for K. This is in definite disagreement with experimental results of Lord Rayleigh[1] who found the definition to be best for $K=0.9$. Evidently best definition and maximum resolving power are not to be had together.

(4) If the quality of the picture given by a pinhole camera is to be as good as that considered satisfactory in making depth-of-field tables for ordinary cameras, the hole-to-plate distance must be at least 45 cm. For a distance of 15 cm, the effective circle of confusion is about twice that for good definition, even with the pinhole of optimum size.

Obviously there must be an optimum diameter for the pinhole for a given hole-to-plate distance. If the hole is too large, any point of the object will produce a large circle of corresponding size with resulting blurring of the picture; if it is too small, the light from every point of the object will be spread out by diffraction to produce equally bad blurring. In between must lie the size that will give the best picture. Some textbooks give a treatment originated by Petzval,[2] which involves the minimizing of the sum of geometrical size and diffraction size. This is unsatisfactory, however, since geometrical considerations have lost all relevance for holes small enough for diffraction to be important. It is necessary to deal entirely with the extension of the diffraction pattern.

The complete theory of Fresnel diffraction at a circular opening has been worked out by Lommel,[3] but the variation of the pattern with changing size of the hole is so complex that there is no simple way in which the complete results can be described. The results for small holes, such as are appropriate for use in pinhole

[1] Rayleigh, Phil. Mag. **31**, 87–99 (1891); *Collected papers*, Vol. III, pp. 429–440.

[2] Petzval, Wien. Sitz. Ber. **26**, 33 (1857); Phil. Mag. **17**, 1–15 (1859).

[3] Lommel, Abh. der Bay. Ak. Wiss. **15**, 233–328 (1886).

cameras, are, however, simple enough to describe in a semi-quantitative way. It is useful to introduce Lommel's variables, y and z, where

$$y=\frac{2\pi}{\lambda}\frac{u+v}{uv}r^2, \quad z=\frac{2\pi}{\lambda}\frac{r\zeta}{v}. \tag{2}$$

Here λ is the wave-length of the light, u is the distance from the source to the edge of the hole, $u+v$ is the distance from the source to the screen, v is almost exactly the distance from the center of the hole to the screen if $r/v \ll 1$ and ζ is the distance to any point on the screen from the center of the diffraction pattern. It gives the size of any feature of the pattern.

If r is eliminated, one obtains

$$\zeta=(z/\sqrt{y})[\lambda v(1+v/u)/2\pi]^{\frac{1}{2}}. \tag{3}$$

Lommel finds the intensity to be a complicated function of the two variables, y and z.

In the following discussion let us assume that λ, u and v are held constant, but that r is varied. Then y is proportional to the area of the hole. It has the value 2π for the outer edge of the first Fresnel zone, 4π for the outer edge of the second, etc. Lommel shows that, for all values of y up to 5.8, the diffraction pattern consists of concentric rings very similar to the more familiar Fraunhofer diffraction pattern given by a circular opening. The first minimum or dark ring comes when $z=3.8$ for all of these values of y, as it does for Fraunhofer diffraction (Fraunhofer diffraction is the limiting case of Fresnel diffraction for $y \doteq 0$). This constancy of z means that, as r and y increase, the radius of the first dark ring [Eq. (3)] decreases inversely as $\sqrt{y}$. The scale of the pattern thus decreases as the hole is made larger. As y increases beyond 5.8, z for the first minimum begins to decrease, the intensity of the central spot continually goes down, and a bright ring with its maximum at $z=3.8$ begins to gain in intensity. At $y=3\pi$ the central spot and the first bright ring have nearly equal intensity. At $y=4\pi$ (second Fresnel zone) the intensity of the central spot has dropped to zero and the greater part of the energy is concentrated in the first bright ring at $z=3.8$. Fig. 1 shows Lommel's results for the intensity as a function of z, for four values of y. In Fig. 2 the intensity is plotted against $\sqrt{\pi z}/\sqrt{y}$. It can be seen from Eq. (3)

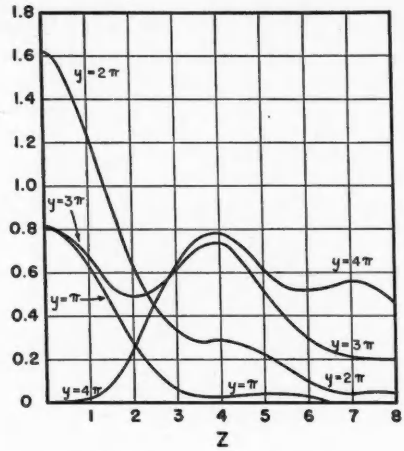


FIG. 1. Intensity as a function of z.

that this quantity is proportional to the actual distance from the center of the diffraction pattern, if y is varied only by changing the radius of the pinhole. Photographs of these patterns are given by Arkadiew[4] and by Mack and Martin.[5] The outer edge of the first bright ring for $y=4\pi$ has a radius only slightly greater than that of the central spot for $y=2\pi$, so that there would be little choice if this were the only consideration. At $y=4\pi$, however, the intensities of the second and third bright rings have risen so that they are comparable to that of the first one, whereas at $y=2\pi$ the intensities of the bright rings surrounding the central spot are relatively low. Thus the pattern is effectively much larger for $y=4\pi$. It becomes more complex and still larger as y is increased above 4π. The problem now is to discover what values of r and y lead to the smallest effective size of the pattern. What we mean by "effective" depends on the criterion we set up for the separability or distinguishability of two such patterns which overlap partially. Since the intensity is a function of y and z, the result for best resolution will be expressed most generally in terms of these variables. In particular, there will be an optimum value of y, which we may express as $y_{\text{opt}}=K\cdot 2\pi$, K being the number of Fresnel zones contained in the optimum pinhole. Putting this in the equation

[4] Arkadiew, Physik. Zeits. **14**, 832–835 (1913).

[5] Mack and Martin, *The photographic process* (McGraw-Hill, 1939), Figs. 2–14, p. 33.

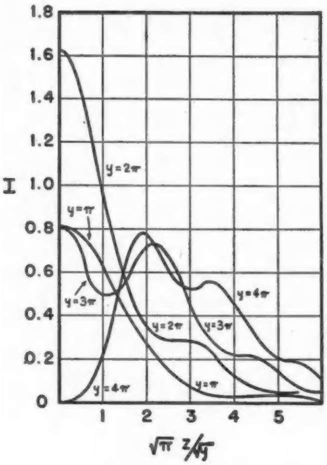


FIG. 2. Intensity as a function of distance from the center of the diffraction pattern.

that defines y, solving for r and multiplying by 2 to get the diameter we obtain Eq. (1), the expression for the optimum diameter of the pinhole.

The numerical value of K remains to be determined. To solve this problem we may turn to the ordinary theory of resolving power. The usual expressions for the resolving power of spectroscopes are based on the assumption that two lines of equal intensity can be resolved when the center of each coincides with the first diffraction minimum of the other (intensity = 0 at minimum), At the point halfway between their centers each line will have an intensity of $4/\pi^2=0.405$. The total intensity there will thus be 0.81. The basic assumption, which is somewhat arbitrary, is that a decrease of less than 19 percent of the intensity will not give an apparent separation of the lines, either when viewed directly or on the photographic plate. My colleague, A. G. Shenstone, has actually obtained slightly better resolution with a prism spectrograph than is thus predicted, showing that this value of 0.81 for the minimum is slightly too low.

For the optical instruments which give circular Fraunhofer diffraction patterns, it is assumed that two points can just be resolved when the central bright spot of each pattern falls on the first dark ring of the other. In this case the minimum of intensity between the two centers comes out to be 0.75, instead of 0.81 as before. This difference emphasizes the approximate and somewhat arbitrary nature of these criteria for resolution. Since they have been borne out by experience well enough, we may take 0.8 as the critical value of the intensity between two maxima of which the intensity is 1. We must find the minimum value of ζ for the separation between the centers of two diffraction patterns so that the intensity midway between them will be no more than 80 percent of that at the centers and will not show any appreciable increase upon further separation.

With this criterion for resolution, let us now consider the Fresnel diffraction patterns. From $y=0$ to $y=5.8$ the situation is like that in the Fraunhofer diffraction. The critical separation is very nearly $z=3.8$, which puts the center of one pattern on the first dark ring of the other. At $y=2\pi$ the bright ring at $z=3.8$ has developed so little that the condition remains unaffected. The relative intensities of the center, dark ring, and first bright ring are 1.62, 0.29, 0.29, respectively. The value $y=3\pi$, however, is already too large. For this value the relative intensities at these positions are 0.81, 0.49 and 0.74. The dark ring is less than 0.8 of the intensity of the nearly equal central spot and bright ring so that the pattern will appear as a spot and ring. The two rings would have to be separated for resolution of the two patterns and the patterns themselves have become too large. Some intermediate value of y must give the optimum radius.

If the relative position of the two systems of rings is such as to bring superposition of opposite sides of the two inner bright rings, a new maximum will be produced in the middle. If this is not to give the appearance of three bright spots in a row, it is necessary that the maximum rise less than 25 percent above the adjacent minima which lie between it and the centers. By interpolation between Lommel's curves for $y=2\pi$ and $y=3\pi$, one finds that this condition is met only for y less than $2.4\pi=7.5$. For this value of y, $z=3$ for the first minimum; z, however, must be about 3.4 for resolution, the minimum not being deep enough upon superposition of two patterns separated by $z=3$. For $y>2.4\pi$, the bright rings would have to be separated for resolution so that the z for minimum separation

would jump to something greater than 4. The minimum value of ζ for separation would go up in proportion and remain larger for all larger values of r. The condition for best resolution of the images of adjacent points is thus $y=2.4\pi$ or $K=1.2$.

Lord Rayleigh[1] considered this problem in a similar way but did not carry the argument quite so far. In comparing the Lommel curves for $y=\pi$ and $y=2\pi$ he remarked, "The latter has decidedly the higher resolving power, but the advantage is to some extent paid for in the greater diffusion of light outside the image proper." This comment seems to indicate that he recognized the question of satisfactory definition to be one which is more complicated than that of mere distinguishability of adjacent points. In his experiments he studied the images of a coarse grating and of round holes when made by different pinholes. He used an orange-red filter with white light, giving a mean wave-length of 6.23×10^{-5} cm, and employed visual observation. The holes corresponded to the following values of y/π: 1.15, 1.50, 1.79, 2.20, 2.78 and 3.49. The definition was decidedly the best for the hole for which y had the value 1.79π. Taking this result of $y=1.8\pi$ for the optimum size he inferred from similar experiments, with photographic observation, that the effective mean wave-length for the plate he had used was 4.2×10^{-5} cm.

Thus, the experimental value for optimum y which corresponds to $K=0.9$ is appreciably lower than the value of $K=1.2$ found in the preceding theoretical treatment. It is perhaps significant that this corresponds very closely to the critical value of $y=5.8$, $K=0.92$ where the first diffraction minimum begins to decrease from its constant value of $z=3.8$. If best definition were to depend upon having a minimum radius for the circle where the intensity has fallen to about 1/7 or less of its value at the central maximum, this result would be obtained theoretically.* From Lommel's curves one can see that the change in the development of the pattern beginning at $y=5.8$ is one which begins to put the circles for intensities of 1/7 or less much farther out, while it does not produce any such great change in those for intensities of about 0.4 which are involved in the ordinary argument concerning resolving power.

The apparent discrepancy between the theoretical and empirical values of K is, of course, of slight practical consequence for the use of the pinhole camera in view of the uncertainty as to the correct mean value of λ to use with modern films. Some new experimental work would be worth while.

When pinholes of proper size are used, the pictures obtained with pinhole cameras are astonishingly good. One may wonder just how good they are. From Eq. (3) one may calculate an approximate value for the diameter of an equivalent or effective circle of confusion. Taking $u\gg v$, $v=15$ cm, $\lambda=4.5\times10^{-5}$ cm, $y=1.8\pi$, $z=3$ (intensity 1/6 of max.), one gets $2\zeta=2.6\times10^{-2}$ cm. The ratio of this to the effective focal length is 1/580, instead of the value 1/1000 which is usually taken as the criterion of satisfactory focus in constructing depth of focus tables. For the pinhole camera this ratio will vary inversely as $\sqrt{v}$. Thus for $v\geqslant45$ cm, and using orthochromatic film and the optimum pinhole diameter, the pinhole camera will give definition equal to, or better than, that considered satisfactory with ordinary cameras. With panchromatic film, the mean value of λ will be greater and the definition for any given length of camera will be less satisfactory.

* *Note added in proof.*—It seems possible that the proper criterion for best photographic definition is that the resolvable separation between edges of extended areas be as small as possible rather than that the resolvable separation between points be a minimum. The newer criterion puts more emphasis on the outer parts of the diffraction patterns as will be shown in a later paper.

Pasteur . . . was a great scientist; but he was not adverse to attacking practical problems—such as the condition of French grapevines or the problems of beer-brewing—and not only solving the immediate difficulty, but also wresting from the practical problem a far-reaching theoretical conclusion, "useless" at the moment, but likely in some unforeseen manner and perhaps at some later time, to be useful.—Abraham Flexner.

On the Presentation of the Thermionic Space-Charge Equation

N. H. Frank
George Eastman Laboratory of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts

CAREFUL and correct derivations of the Langmuir-Child equation giving the space-charge limited current between plane parallel electrodes as a function of anode potential, together with critical discussions as to the nature of the approximations involved, are to be found in a number of books.[1] Nevertheless, there is a disturbing tendency on the part of many writers of books on electricity—especially recent books—to present the derivation without critical discussion or to use arguments that leave even the serious student with erroneous ideas concerning the true character of the equation unless the treatment is supplemented with extended critical discussion on the part of the instructor. Therefore, it seems appropriate to summarize briefly the fundamental aspects of the problem so that its presentation to students may leave them with a correct picture of the physical phenomena involved.

It will be helpful to review briefly the steps in the argument. One starts with the Poisson equation in one dimension,

$$d^2V/dx^2 = 4\pi ne/\epsilon_0, \qquad (1)$$

in which V is the potential at a distance x from the hot cathode, n is the density of electrons at any point in this plane, e is the absolute value of the electronic charge and ϵ_0 is the permittivity of empty space. The speed v (normal to the electrodes) of an electron is related to the potential by the equation

$$\tfrac{1}{2}mv^2 - eV = \tfrac{1}{2}mv_0^2, \qquad (2)$$

where v_0 is the initial speed of the electron as it leaves the cathode. In the customary treatment one neglects this initial speed and writes, in place of Eq. (2),

$$\tfrac{1}{2}mv^2 = eV. \qquad (2a)$$

Furthermore, the magnitude of the current density j in the steady state is related to the electron speed by

$$j = nev, \qquad (3)$$

since all electrons in a given plane have identical speeds if $v_0=0$. From Eqs. (2a) and (3) one expresses n in terms of V, inserts this value in Eq. (1) and integrates once, obtaining

$$(dV/dx)^2 - (dV/dx)_0^2 = (8\pi/\epsilon_0)j(2m/e)^{\frac{1}{2}}V^{\frac{1}{2}}, \qquad (4)$$

where $-(dV/dx)_0$ is the field strength at the cathode. Now we come to the crucial point in the discussion. The next step is to place $(dV/dx)_0$ equal to zero. Further integration then yields the well-known form of the Langmuir-Child equation,

$$j = (\epsilon_0/9\pi)(2e/m)^{\frac{1}{2}}(V^{\frac{3}{2}}/d^2), \qquad (5)$$

where V_0 is the anode potential and d is the electrode separation.

The presentations to which the author objects adopt one of two attitudes in justifying the step of placing the field equal to zero at the cathode. First, one finds a bald statement of the sort, "assuming the field to be zero at the cathode"; this is obviously unsatisfactory, especially in view of the entirely incorrect physical picture to which the equations lead if examined critically, as we shall do in a moment. Second, the following type of argument is employed:

> Consider a fixed anode potential V_0 and suppose that the cathode temperature is so low that the saturation current is very small. In this case the density of electrons at any point will be so small that the potential will vary almost linearly with distance from the cathode. Since the right-hand member of Eq. (1) is always positive, the curve of potential as a function of x must be everywhere concave upwards. Now, as the cathode temperature is increased, the current will increase and this curve will become more and more concave upwards until eventually it starts at the cathode with zero slope. Further increase of cathode temperature will not produce an increase in current and the current becomes limited by space charge.

This reasoning is correct but implies that the condition of zero field at the cathode corresponds to the transition from saturation to space-charge limited current. It is fallacious to insist that Eq.

[1] For example, O. W. Richardson, *The emission of electricity from hot bodies* (ed. 2), pp. 69ff; J. J. and G. P. Thomson, *Conduction of electricity through gases* (ed. 3), vol. 1, pp. 371ff; K. K. Darrow, *Electrical phenomena in gases*, pp. 321ff.

(5) so derived, and without further justification, should be expected to give the variation of current with potential at *constant* cathode temperature in the region of space-charge limited current. This becomes clear when one remembers that the force acting on an electron at any point between cathode and anode is directed toward the anode with the result that every electron leaving the cathode (with a small but finite speed) must reach the anode, so that saturation current exists.

Evidently, if a steady, unsaturated current is to exist, some of the electrons leaving the cathode must return to it and one must introduce the mechanism by which this occurs. This is, of course, the appearance of a potential minimum in the space between the electrodes and the consequent fact that the force acting on electrons at the cathode must be directed *toward* the cathode, opposite to the direction of the electron current. It now becomes evident that, for the case of space-charge limited currents, the assumption of completely negligible speeds of emission of the electrons is inadequate. Furthermore, there must be a distribution of these velocities, as otherwise all the electrons would be able to pass through the potential minimum or all would return to the cathode (at least on the basis of classical mechanics). Now, for a range of relatively high anode potentials V_0, the position of the potential minimum is close to the cathode, does not vary much with V_0 and its depth is small compared to V_0. Hence, for this range, Eq. (5) will be a good approximation if d is taken to represent the distance from the potential minimum to the anode, and V_0, the difference between the anode potential and the minimum value of the potential. Identification of V_0 with the potential difference between anode and cathode and of d with the electrode separation then affords a somewhat rougher approximation. Despite the desirability of neglecting initial velocities for the purpose of simplifying the mathematical treatment of the problem, it is essential to introduce them—at least qualitatively—in order to understand how space-charge limited currents can exist at all. The physical arguments which should accompany any derivation of the Langmuir-Child equation are essential in justifying the neglect of the initial kinetic energies of the electrons in the mathematical formulation of the problem.

The Remodeled Physics Laboratory at Bryn Mawr College

WALTER C. MICHELS AND A. L. PATTERSON
Department of Physics, Bryn Mawr College, Bryn Mawr, Pennsylvania

As part of a program for increasing the facilities available for the sciences at Bryn Mawr College, the remodeling of the first floor and basement of Dalton Hall was undertaken to provide more adequate laboratories for the Department of Physics. This building, completed in 1893, is of slow-burning mill construction with masonry exterior and bearing walls. The space available for the physics laboratory consisted of most of two floors of approximately 5000 ft^2 each. Of this space nearly all of the first floor and a few rooms in the basement originally had been designed and already were in use as a physics laboratory. The remainder of the basement had been used principally for storage, was unfinished, and lacked adequate lighting and ventilation. A portion of the basement was allotted to existing heating services and to an instrument-maker's shop which serves five science departments. The remodeling problem was complicated by the fact that the funds available were limited. It was therefore impossible to alter structural walls.

The necessary accommodations could be classified roughly under four heads: (1) lecture room and laboratory for a general physics course limited to 40 students; (2) classrooms and laboratories for advanced courses of not more than 10 students each; (3) research facilities for staff and graduate students; (4) library and reading room with shelf space for the present 5000 volumes and an expansion allowance of about 50 percent. For convenience, it was decided to locate the classrooms, offices, library and laboratories for the larger classes on the first floor. Advanced undergraduate laboratories and research

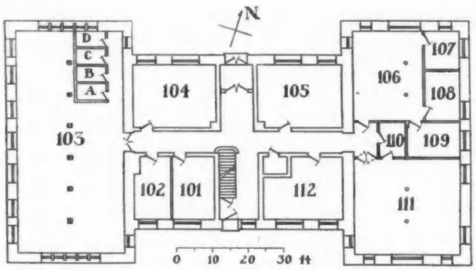


FIG. 1. Floor plan, first floor: *101*, small classroom (11 seats); *102*, photographic and optics laboratory for first- and second-year work; *103*, first-year laboratory (general physics); working positions are provided with gas and d.c. convenience outlets; 13 of these positions can also be connected to the laboratory switchboard; *A*, *B*, *C*, *D*, sound and optics rooms; *104*, second-year laboratory; *105*, preparation and apparatus storeroom; *106*, library and reading room; *107*, *108*, *109*, faculty offices; *110*, apparatus storeroom; *111*, lecture room (52 seats); *112*, graduate seminary room and periodical room. Rooms *101* and *111* are fully equipped for demonstration lectures. The switchboard panels in rooms *105* and *111* are connected in parallel to facilitate the preparation of demonstrations for the larger classes.

rooms were concentrated in the basement area.

The floor plans finally adopted are shown in Figs. 1 and 2. All of the heavy walls shown in these plans are structural elements, as are the brick and cast-iron columns spaced through the centers of both wings. In utilizing space in the wings, some convenience of access to rooms was sacrificed by eliminating corridors as much as possible. It will be noticed that those rooms whose functions require that they be darkened are located in those parts of the basement which are without windows. Mechanical ventilation is provided for these rooms. The contour of the ground is such that the east end of the basement is at ground level. Sodded areas are provided on the other three sides of the building for lighting and ventilation.

On the first floor a number of old partitions were removed and only a very few feet of new partitions were built. Some of the old matchboard partitions on this floor were covered with Sheetrock and plaster. The partitions in the light and sound rooms of the first-year laboratory (*103*) were erected of unpainted Celotex on staggered 2×3-in. studding. This has proved fairly effective for sound insulation. In the basement almost all partitions are new. Since termite attacks have become prevalent in this district, these partitions were constructed of 4-in. hollow tile, and wood frames and trim were eliminated as far as possible. Cypress nailing strips (2×6 in.) similar to those used at Washington University[1] were mounted at heights of approximately 34 and 84 in. around the walls of all laboratories on this floor to facilitate the attachment of apparatus. The concrete floors of the basement were covered with asphalt tile.

The entire laboratory was rewired. Class and lecture rooms were lighted with luminous globe indirect fixtures, and semi-indirect lighting was used in most of the other rooms. A general illumination level of 15–20 footcandles is provided throughout with the intention that local lighting be used wherever higher intensities may be necessary. A large number of a.c. and d.c. convenience outlets is provided in all laboratories. These are grouped eight outlets to a 20-amp circuit with the expectation that individual outlets will not be used for more than 5 amp. All heavier loads are drawn from the laboratory switchboard from which 2 to 10 wires (No. 10 B & S) run to each laboratory. These wires terminate at the load end in 25-amp inverse time magnetic breakers.[2] At the switchboard end, jacks to these lines are grouped by rooms in a single "outgoing" panel. Feeders (50 amp) are brought to a second panel of the board to supply

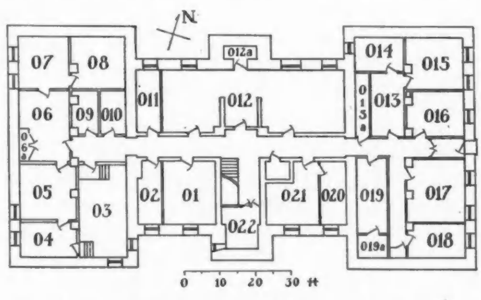


FIG. 2. Floor plan, basement: *01*, women's room; *02*, *011*, *013a*, *020*, heating services; *03*, advanced electrical laboratory; *04*, *015*, *016*, *017*, *021*, research rooms; *05*, *06*, advanced optics laboratory (gas, water, steam and electrical services enter at *06a*); *07*, *08*, x-ray research laboratory; *09*, photographic dark-room; *010*, densitometer room; *012*, Instrument-maker's shop; *012a*, storage vault (Dept. of Biology); *013*, staff and students shop; *014*, glass-blowing room; *018*, storage room (Dept. of Biology); *019*, switchboard room (also contains air compressor and motor generator for 500–1000 v d.c.); *019a*, storage battery (50 cells); *022*, men's room.

[1] C. F. Hagenow, Am. J. Phys. (Am. Phys. Teacher) 3, 25 (1935).

[2] Supplied by Heinemann Electric Co., Trenton, N. J.

110–220 v d.c. from the college power plant and 110–220 v a.c. from the Philadelphia Electric Company. A storage battery of 50 cells is divided into isolated banks of 5 cells each, and these are connected separately to the same panel. The two end banks are tapped between cells. Special bipolar plugs are used to connect these banks in series, and are so designed that no cell or group of cells can be short-circuited at the board. This panel is also equipped with a 1000-w transformer to provide low voltage a.c. (4–24 v by 4-v steps). A third panel carries the controls of the battery charging circuit on which a fan for ventilating the battery room is floated. This panel also includes jacks by means of which a 500–1000-v d.c. generator may be connected to the research rooms. The wiring system for this supply is entirely isolated, and special jacks are used for connection to it.

At a number of points in each laboratory, electric, gas, water and compressed air outlets, as well as drains, are grouped together to form a "station." A standard relative arrangement of outlets was used throughout the laboratory. At one such station in each room is located the panel carrying the incoming leads from the switchboard. At some of the other stations two or four lines from the room panel terminate in binding posts. The drainage lines,[3] which empty into the sinks, consist of 1-in. galvanized pipe laid along the top of the lower nailing strip. At each station a 1×2-in. socket opens into these lines. The water outlets are mounted directly above these sockets. A complete station is illustrated in Fig. 3. Whenever possible, plumbing lines end in tee connections, rather than elbows or caps, to allow easy extension.

The exact cost of the alterations cannot be given, as the work done in the physics laboratory formed only a part of that done on Dalton Hall as a whole. For the work done on these two floors the approximate cost was $19,000 divided as follows:

Construction	$5000
Plumbing, heating and ventilating	4500
General electrical wiring and fixtures	2300
Painting	1200
Laboratory wiring system (including installation)	3500
Other equipment and furniture	2500

[3] Similar to those used in the Palmer Physical Laboratory, Princeton University.

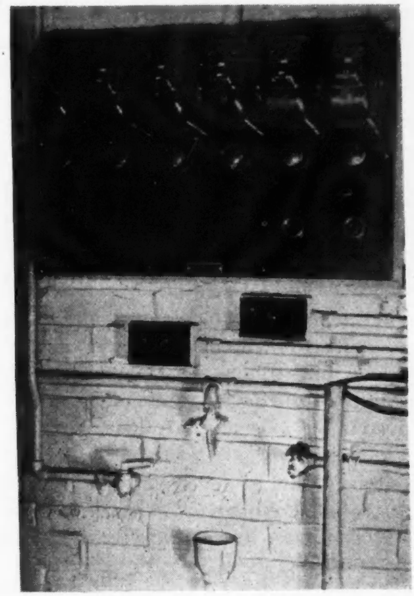


FIG. 3. Complete "station" layout. On the room panel at the top may be seen the magnetic breakers and binding posts terminating the lines from the switchboard. The special high-voltage terminals are in the lower right-hand corner of this panel. Below, in vertical order, are the 110-v d.c. outlet, the 110-v a.c. outlet, and the water, gas and compressed air taps. At the bottom is shown the socket of a drainage line.

The equipment cost represents a relatively small part of the total since it was possible to rebuild and use much of the existing fixtures and furniture.

The general contractor was the Robert E. Lamb Company. The electrical work was installed by Cates and Sheppard, and the plumbing, heating and ventilating by Wm. H. Walters and Sons. The equipment for the laboratory wiring system was furnished by the Standard Electric Time Company.

It is a pleasure to express our gratitude for a bequest of the late Sophie Boucher and for gifts from members of the Board of Directors of Bryn Mawr College which made this work possible. Special thanks are due to Mr. Francis J. Stokes, Chairman of the Committee on Buildings and Grounds of the Board, whose enthusiastic interest and valuable experience led to the successful solution of a very difficult problem.

Reproductions of Prints, Drawings and Paintings of Interest in the History of Physics

10. Gillray's Caricature of Count Rumford

E. C. WATSON
California Institute of Technology, Pasadena, California

BENJAMIN THOMPSON, COUNT RUMFORD (1753–1814), like his contemporary[1] BENJAMIN FRANKLIN (1706–1790), made important improvements in the construction of fireplaces, chimney flues and kitchen utensils. His attention was first directed to such matters by his organization of relief work among the poor in München and his attempts to produce cheap and nutritious food. Many of the devices and conveniences now employed in our kitchens owe their origin to him. So great, indeed, was his interest in these and allied subjects that he devoted five of his eighteen *Essays, Political, Economical, and Philosophical*[2] to them. These five essays, with titles as follows,

Essay IV, "Chimney Fireplaces, with proposals for improving them to save Fuel; to render Dwelling-houses more comfortable and salubrious, and effectually to prevent Chimneys from smoking,"

Essay VI, "Of the Management of Fire and the Economy of Fuel,"

Essay X, "On the Construction of Kitchen Fireplaces and Kitchen Utensils; together with Remarks and Observations relating to the various Processes of Cookery, and Proposals for improving that most useful Art,"

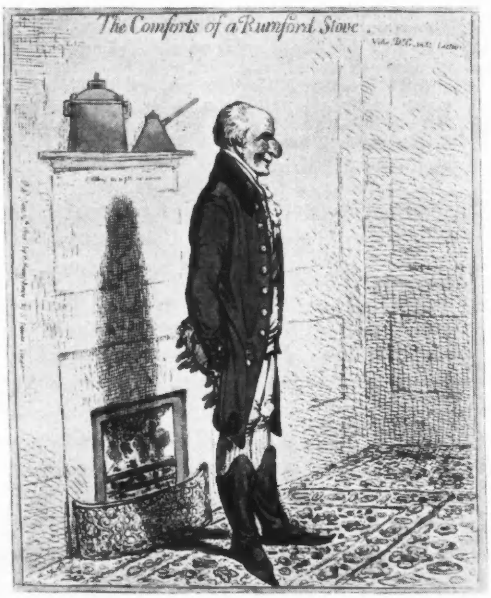
Essay XI, "Supplementary Observations concerning Chimney Fireplaces,"

Essay XIV, "Supplementary Observations relating to the Management of Fires in closed Fireplaces,"

occupy nearly 600 pages in his *Complete Works*[3] and make most interesting reading. He reports, for example, that at one time he had not less than 500 smoky chimneys on his hands and proceeds to give very simple and intelligible information about the philosophic principles of combustion, ventilation and draughts and to prepare careful diagrams showing the proper measurements, disposal and arrangements of all parts of a fireplace and flue. His aid and advice were always ready and were given indiscriminately to all sorts and conditions of men. The immediate fame which this type of work brought RUMFORD has been recorded by PETER PINDAR (JOHN WOLCOT) as follows:[4]

Muse, at the sound of "Rumford" *raise* thy voice,
And bid our Kitchen-furniture rejoice.—
Though scant our store, a hempen String (alack!
The simple substitute for spit and jack),
A knife and Fork, a Dish, a Spoon, and Platter,
Shall stir their stumps, and make a jovial clatter;
The Broom shall hop, as merry as a grig;
And, pleased, the dainty Dishclout dance a jig;
Expressing thus in *gratitude* their souls
To him whose wisdom saves us *pecks* of coals,
And means (for Pitt's damn'd taxes this require)
To teach us soon to roast *without a fire* . . .

Knight of the Dishclout, whereso'er I walk,
I hear thee, Rumford, all the kitchen-talk:
Note of melodious cadence on the ear,
Loud echoes "Rumford" here and "Rumford," there.



Caricature of Count Rumford by James Gillray.

[1] The similarity between the colorful careers of these two famous Americans has been pointed out by G. E. Ellis in his *Memoir of Sir Benjamin Thompson, Count Rumford* (Macmillan, 1876).

[2] First English edition (London 1796–1812); first American edition (Boston, 1798–1802), 3 vol.

[3] Macmillan, 1876, 4 vol.

[4] "A poetical epistle to Benjamin Count Rumford," *The works of Peter Pindar, Esq.* (London, 1812), Vol. 5, pp. 130–131.

Lo, every parlour, drawing-room, I see,
Boasts of thy stoves, and talks of naught but thee.
Yet not alone my Lady and young Misses,
The Cooks themselves could smother thee with kisses:
Yes; Mistress Cook would spoil a goose, or steak,
To twine her greasy arms around thy neck.
Through Newspaper, through Magazine, Review,
Happy mine eyes thy splended track pursue;
Thy sage Opinion in each Journal read,
A vein of Silver 'midst a load of Lead.

The amusing caricature here reproduced tells the same story. The original is a brightly colored print ($7\frac{3}{4}\times 9\frac{3}{4}$ in.) executed by JAMES GILLRAY (1757–1815), one of the greatest of English caricaturists. It was published on June 12, 1800, by H. Humphrey and sold in her print shop in St. James's Street, London.

On the Teaching of Newton's Second Law of Motion

J. EDWARD SPIKE, JR.
Science Department, Manter Hall School, Cambridge, Massachusetts

THE recent discussion on the use of constants in physical laws may be reviewed in its several phases by starting with the criticism of a section on units in Osgood's *Mechanics* as contained in a book review published in *Science*.[1] These comments were augmented and intensified in an article by Dadourian[2] which is of interest because it gives a clear statement of the issues involved: "questions of consistency of notation, simplicity of mathematical expressions of physical laws and the significance of the symbol m." Recently, in this Journal,[3] Dadourian amplified his views in a literary masterpiece of unusual charm.

There is still one important issue which I feel has been almost universally overlooked: how the subject can be most successfully presented to the student. It seems that physics teachers are divided into two groups on the matter of how the equation expressing Newton's second law of motion should be written. In the three articles already cited we find it stated that the constant k should not be used; but in an article[4] appearing only a few months after Dadourian's first discussion, we find a teacher at the same college pointing out the advantages of $F_g=kma$. And finally, there appeared a fourth article[5] which seems to have been contributed by a teacher who feels the pulse of the classroom. Here the approach is made without the constant k, and with the aid of a table showing all the possible units in all systems.

Bearing in mind that one of the foremost criterions of the physics teacher should be that of imparting to the student the necessary information as clearly and easily as possible, let us look at some of the methods of presentation of recent origin which have been widely accepted. Both the dramatization and popularization of physics are recent. *From Galileo to Cosmic Rays*[6] has shown that a whole textbook may be built on the graphic principle. In fact, it now seems possible to carry this idea to an even greater degree. Likewise, the wide popularity of *The Evolution of Physics*,[7] in which Einstein has put forth a scientific thesis at a popular level, has done much to eliminate the cry of "undignified" with respect to similar presentations.

METHODS OF CLARIFYING THE CONCEPTS

The problem of teaching the concept of mass is complicated by the fact that on some occasions mass may be expressed in *pounds* while at other times it may be expressed in *slugs*. To eliminate some of the confusion for the beginner, Worthington[8] proposed to write "pound" for the unit of force, and "lb" for the mass unit. More recently, Saunders[9] modified this practice by using

[1] Campbell, Science **86**, 441 (1937).
[2] Dadourian, Science **87**, 388 (1938).
[3] Dadourian, Am. Phys. Teacher **7**, 241 (1939).
[4] Perkins, Science **88**, 353 (1938).
[5] Beardsley, Science **89**, 58 (1939).
[6] Lemon, *From Galileo to cosmic rays* (Univ. of Chicago Press, 1934).
[7] Einstein and Infeld, *Evolution of physics* (Simon & Schuster, 1938).
[8] Worthington, *Dynamics of rotation* (Longmans, Green, 1925), p. 9.
[9] Saunders, *Survey of physics* (Holt, 1936), p. 65.

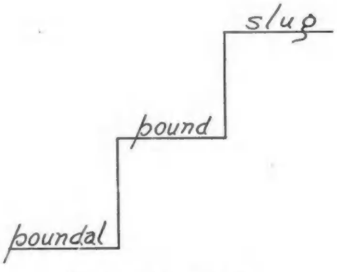


FIG. 1. The "stairs."

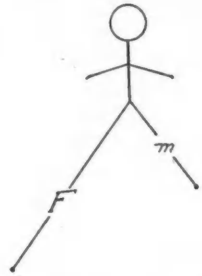


FIG. 2. The "man."

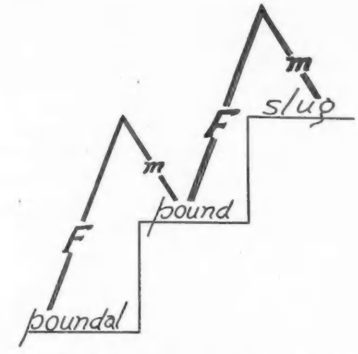


FIG. 3. Legend for colors: —, black; =, red; ≡, green.

"lb" for the pound of force, and "pd" for the pound of mass. This has been some help to the students.

There are two practices which, although in common use, seem to work to the disadvantage of the student: one is to use the equation $F/W=a/g$; the other, to substitute W/g for m in any equation. These eliminate explicit consideration of the mass concept, and by avoiding the issue much understanding may be lost. If, on the other hand, we try to untangle the mass concept from the force concept we may use the suggestion of Bridgman,[10] who considers the case of a body placed in space far enough away from any other body so that the gravitational attraction is zero. If, then, to this body we desire to impart an acceleration, we must apply a force. This force is applied to a weightless body; hence the mass concept becomes isolated. I have found an example of a "pound package of sugar" to be effective. Consider the case of such a package on the table before the student. Its weight is marked on it. A class estimate of the number of cups of coffee that can be sweetened by it is obtained. Then it is proposed to remove the same package 4000 mi from the earth's surface. Its weight is then asked, and a new estimate of its sweetening ability requested. It is soon realized that the latter property is independent of gravity but related to the mass concept.

A Diagrammatic Approach

From this point we might treat the formula according to Beardsley's[5] method. However, I notice that this fails to make a deep impression on the students; a more outstanding treatment along the lines of Lemon's[6] graphical method should be better. But it will be necessary to extend the presentation to cover all the units in the several systems as given in "Table 1" of Beardsley's article; hence, let us start with the second law in the form $F=ma$. It is possible at this point to introduce proper units and follow with the check of dimensions, but it has seemed better in practice to reserve this for a later time when the student has mastered the concepts and the use of the formula, and can then turn to dimensions as a real "check."

Consider, for the moment, only the English system of units. Fig. 1 is a simple diagram showing three terms resting on what the students have called "the stairs"; the psychological implication of the higher positions of the *pound* and *slug*, respectively, is seldom overlooked by a student. The next step is to introduce the "man" who will stand on the "stairs" (Fig. 2). In order to emphasize the peculiar structure of the "creature," I find it helpful to relate a story about a mythical animal that could run around a conical mountain in only one direction because the legs on one side of its body were longer than those on the other. In a similar manner, the "man" with the asymmetrical legs is designed to stand only with his feet on adjacent stairs. It will be noted that the shorter leg is labeled m and the longer one, F.

Now comes the question as to the number of positions the "man" can occupy on our flight of three steps. Obviously, there are only two. So we diagram this information, combining Fig. 2,

[10] Bridgman, *Logic of modern physics* (Macmillan, 1928), p. 102 ff.

leaving off the body portion which serves no purpose, with Fig. 1, and thereby obtain Fig. 3. If this is done in color, as indicated by the legend, a better impression is created. The fact that the green figure represents the English gravitational system may be pointed out, if desired.

From Fig. 3, we observe that the poundal is the unit of force in the red system and that the pound is the unit of mass in this system. Likewise, the proper units in the green system are symmetrically placed. To complete the picture we must relate poundals to pounds, etc. We know 32, approximately, to be the factor that is the multiple in both cases. Thus, in Fig. 4, 32 has been put on the risers of the "stairs." Conversion factors are usually a source of trouble, and a short drill on a very simple example can be helpful at this point. To eliminate as much difficulty as possible, two arrows are added to complete the figure; they indicate that when changing stairs all that is necessary is to divide on going up and multiply on coming down. With this detailed account of procedure for the English system, we similarly construct a set of stairs for the metric units. This completes the diagram (Fig. 4).

Beardsley,[5] in his Table 1, and other authors have used the term "metric slug" to denote a unit of mass in the metric gravitational system. Besides adding to the symmetry of the system of units, the unit is sometimes used in practice. I have named this unit the *par*. In this connection I looked up the origin of the term *slug* and found in *Nature*[11] the following statement, "The author [A. M. Worthington] introduces the name *slug* to denote mass. . . ." This comment was made in a book review of the revised edition of *Dynamics of Rotation*, first published in 1891. Worthington,[8] in a recent edition of the same text, adds: "It is convenient to give a name to this practical unit of inertia or sluggishness. We shall call it a *slug*." Since the word *sluggish* had been reduced to *slug*, what could be more fitting than to take a French synonym, *paresseux*, and reduce it to *par?* This term is preferred to "metric slug" because of its monosyllabic form and also because it carries no previous connotation.

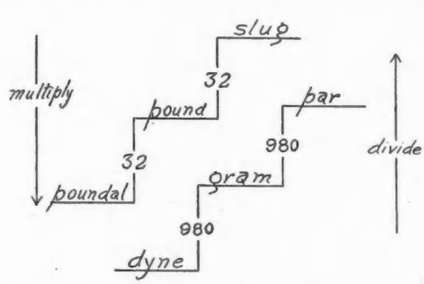


FIG. 4. The final diagram.

[11] Anon., Nature 67, 351 (1903).

Within a very short time, the student becomes familiar with Fig. 4, and its utility. I shall point out its advantage by suggesting two problems.

Problem 1. A body weighing 16 lb rests on a frictionless table and is tied by a light string to an 8.0-lb weight which hangs over the edge of the table, the string passing over a frictionless pulley. What is the acceleration when the weight is released?

Since it is acceleration that is desired, there is no advantage in using one system in preference to the other. Either the unit of F or that of m must be changed before substituting in the formula, $F=ma$. The only difficulty which the student may experience will arise from failure to take into account the fact that the two weights are *tied together*.

Let us change the problem slightly and see the result.

Problem 2. If, in the preceding problem, the weight of 8.0 lb gives the system an acceleration of 11 ft/sec^2, what is the mass of the body on the table?

Here we are to determine a *mass* and this may be expressed either in pounds or in slugs. Usually an answer in pounds will be given. This at once directs the choice of the green, or lower system, and so we change the "8.0 lb" into poundals before substituting in the formula. This second problem shows that at times it is desirable to use one system in preference to another.

Admittedly, this method is purely a teaching aid, and a transient one at that; the student soon becomes acquainted with both concepts and units, and has little need for the system in detail. However, one test of any teaching method is term examinations, and the fact that this method has repeatedly enabled substandard students to understand a phase of physics that often confuses good students has caused me to continue its general use. Obviously, this same scheme can be used without modification in the study of the dynamics of rotation.

This article does not contribute to solving the argument as to whether Newton's second law should be written with or without the constant k. But it does give the beginner a systematized procedure which can serve him while he is learning new concepts.

A REPORT OF THE COMMITTEE ON THE TRAINING OF PHYSICISTS FOR INDUSTRY

Suggested Four-Year Curriculum Leading to a Major in Physics

THIS report is a continuation of the reports submitted by the Committee on the Training of Physicists for Industry to the American Association of Physics Teachers on December 31, 1936, and December 27, 1937. The latter report[1] dealt with the conclusions and recommendations of the committee concerning students who will take a Bachelor of Science course with a higher concentration in physics than is implied in the usual major in physics course. It included consideration of the students who take courses of study sometimes designated as "applied physics" or "engineering physics."

The present report concerns students who will take a more general course, which may be designated as a "major in physics," either at institutions where the opportunities for both this and the course of higher concentration are available, or at institutions where only the former is available. Obviously this report pertains largely to circumstances as they exist in most of our liberal arts colleges.

While it is quite gratuitous and unnecessary to justify here the traditional teaching of physics in our liberal arts colleges, it is not inappropriate to point out that the more intimate contact between teacher and student in these colleges does, evidently, lead to a greater stimulation of student interest than is found in our large institutions, for to a striking extent the graduate schools of physics are fed from the liberal arts colleges. This fact alone is sufficient to point the importance of the questions under study by the committee, and at the same time is a tribute to the high character of the work being done in physics in these colleges, frequently under difficult conditions.

Specifically, the purpose of this report is to reflect the deliberations of the committee and to make recommendations concerning the curricular requirements to be associated with the term *major in physics*. To provide a wider representation from the liberal arts colleges than the general committee afforded, a subcommittee was appointed as follows, and the general committee is largely indebted to these gentlemen for the material of this report:

C. R. Fountain, *Peabody College*
G. P. Harnwell, *University of Pennsylvania*
F. G. Tucker, *Oberlin College*
S. R. Williams, *Amherst College*
L. A. DuBridge, *University of Rochester*[2]
R. A. Patterson, *Rensselaer Polytechnic Institute*[2]
P. I. Wold, *Union College*[2]

While it would have been desirable to obtain the opinions of some hundreds of college teachers of physics, this has not been possible. However, the report may be said to represent the integrated opinion of some twenty representative teachers from rather widely scattered institutions. It is gratifying to learn that on certain points there is good agreement.

Parts of the report of December, 1937, relating to students taking a B.S. in Physics course,[1] are pertinent also to the group of students with which the present report is concerned. There it was stated that the purposes of a course leading to a degree of B.S. in Physics should be

(1) To impart to students scientific curiosity and enthusiasm for work in physics.

(2) To give them a thorough training in the fundamentals of physical science.

Surely none would take exception to these statements as being equally appropriate to majors in physics, and a teacher of physics would have these always in mind.

There the opinion was also expressed that "Personality, character and innate ability are the primary characteristics which determine a student's success in and usefulness to society, factors over which teachers in college physics have little or no control." Certainly this holds here. It may be added, however, that, little as the control may be, no teacher would permit himself to neglect any opportunity to contribute constructively to the implementing of character building on the part of the student; he would, indeed, feel that he had largely failed in his mission if he had not contributed to it. Is there any reason to believe that the sciences them-

[1] Am. J. Phys. (Am. Phys. Teacher) **6**, 82–84 (1938).

[2] Representatives from the general committee.

selves are lacking in the opportunity which they afford teachers for such contributions? Hardly so, for personal struggles with a difficult problem, or with a defying piece of research, undoubtedly carry values of the highest significance. Is there any reason to believe, then, that the sciences *per se* are not disciplines of mental and spiritual values as stimulating in their purposeful objectives as are other branches of learning?

In the discussions leading to this report, there was expressed repeatedly the recognition of the items just referred to, but there was also a unanimity of feeling that there should be ample opportunity for a broad cultural education. This does not for a moment exclude the sciences in general or physics in particular as of cultural value. On the contrary, it is recognized that "learning is comprised of many parts, *including the laws of nature*, and culture is the one indivisible whole made up of these parts." Whether it is possible in the time at the student's disposal to get in as many of the broadening courses as many teachers will recommend, and at the same time to take the courses closely related to the student's major, which the same teachers strongly urge, is open to question. Any solution must, no doubt, be a compromise, and any recommendations made by this committee must be interpreted liberally.

The conclusions of the committee with regard to specific questions may be stated as follows:

(1) Recommendations, bearing the stamp of approval of the American Association of Physics Teacher, for a curriculum for physics majors would be desirable, but they should be very elastic in order to allow for the great variations in individuals and in the types of liberal arts colleges.

(2) There was a feeling that the usual requirements for the baccalaureate degree in most of our colleges insure sufficient work in the nonscientific fields, such as history, literature, languages, philosophy, etc. All were agreed on the need for emphasis upon the importance of written and spoken English.

(3) Opinion was unanimous that the work in mathematics should include elementary calculus and differential equations as a minimum.

(4) A majority opinion strongly recommended three years of chemistry—general, organic and physical.

(5) There was general agreement that major work in physics should include intermediate courses in theoretical mechanics, electricity and magnetism, optics, thermodynamics and modern physics. Several of these would, no doubt, be one-semester courses.

(6) There was practical unanimity of opinion that the history of science broadly and the foundation of physics more specifically should be covered by individual reading rather than by special courses. There was also a feeling that, except for the unusual student, reading assignments relating to these had best be postponed to the junior and senior years.

TABLE I. *Semester hours allotted to different subjects.*

Field	Subject	Semester Hours
Physics	General college course	10
	Intermediate courses *selected* from:	
	Theoretical mechanics	6
	Heat	3
	Electricity and magnetism	6
	Sound	3
	Optics	4
	Modern physics	4
	Electrical engineering	6
Mathematics	Basic courses in advanced algebra, trigonometry and solid geometry	6
	Calculus	6
	Differential equations	6
	Vector analysis or advanced calculus	6
Chemistry	General	8
	Organic	4
	Physical	6
General	A wide latitude is desirable with emphasis on English and English composition, history, one or more languages, economics, philosophy and sciences other than physics	

In discussions of this nature, it is natural that special attention should be paid to the basic course in general physics, given during the freshman or sophomore year, from which students acquire their inspiration and enthusiasm for physics, or else learn that physics, as a major subject, is not for them. It is desirable that a first course should be of an intensive character, intensive in the sense not of being encyclopedic but of containing close analysis of principles and much drill in problems; the kind of course that is usually available in institutions where there are many engineering students and where the first course is adapted to these students. In institutions where there can be but one first course for all students, it must be designed to meet the needs, first of the nonmajors, and second of the majors. In this case the emphasis will be placed on making the course "cultural." It will be cultural to the extent that it helps the student to comprehend the modern scientific world-picture. But for the major, physics must be made to be more than this—a fact that must be borne in mind in the planning of subsequent courses. If, from necessity, the first course is largely qualitative, then any defect in extended quantitative knowledge or experience must be

made up in subsequent courses in order to develop an intuitive sense and an appreciation of physical relationships and analytic skill. These come only by sustained and close contact with the subject, and adequate time must be allowed for acquiring them.

The following percentages are representative of the opinion of the committee in the matter of the broad proportioning of time in a four-year course of 130 semester hours:

	Minimum	Average
Physics	20%	25%
Mathematics	15%	20%
Chemistry	15%	20%
General	50%	35%

Within the four sections the proportioning could well be made up substantially as indicated in Table I.

The choice of intermediate and advanced courses to be made available in a given institution should depend, to a considerable extent, on the teaching staff—on its individual personal interests and fields of productive scholarship; for in such fields will there be realized the finest personalized teacher-student relations.

This report is concluded with the qualifying statement that no hard and fast recommendations should be made as to the "best" or even the preferred courses to be recommended for the students whom this committee has in mind, because:

(1) The courses which are available for students differ so greatly from institution to institution that, even were there unanimity of opinion as to what courses should be taken by these students, it would be impracticable to offer them uniformly, at least not without considerable and long-time changes in many of the colleges;

(2) The diversity of opinion within the body of physics teachers as to courses and content of courses is so great as to preclude any hard and fast agreement on such a subject; and

(3) This diversity of opinion—at least to the extent that it results from thoughtful experience and experimentation—is not a thing to be discouraged; on the contrary, it may be a sign of health and vigor in our field of science. Probably all would agree that it would be most unfortunate if the physics courses, as offered and as taught, were all cast in one mold for all institutions.

The Committee on the Training of Physicists for Industry of the American Association of Physics Teachers.—H. A. Barton, G. A. Campbell, Harvey N. Davis, H. L. Dodge, L. A. DuBridge, G. R. Harrison, A. W. Hull, F. G. Keyes, R. von Nardroff, R. A. Patterson, W. Wilson, A. G. Worthing, P. I. Wold, *Chairman.*

Measurement of the Charge-Mass Ratio of Electrons Thermionically

F. Malcolm Gager
Department of Physics, Boston College, Chestnut Hill, Massachusetts

Langmuir[1] has shown a general law relating the current and voltage between a copiously emitting cathode and a non-emitting anode situated in a vacuum and maintained at a difference of potential. The particular relation is the three-halves power law,

$$I_p = KE_p^{3/2}. \tag{1}$$

Theoretically and experimentally it is evident that K is different for different electrode configurations, and to date there are but three K's, two practical, that are expressible in a formal manner. By setting up Poisson's equation, $\nabla^2\phi = 4\pi\rho$, for a parallel plate structure, Child[2] found the relation between the space current per unit of area of emitting surface for plates infinite in extent to be

$$I_p = \frac{(2e/m)^{1/2}}{9\pi s^2} E_p^{3/2} \text{ esu.} \tag{2}$$

By similar reasoning on symmetrically arranged concentric cylinders, also infinite in extent and the inner one the cathode, Langmuir[1] determined

[1] Langmuir, Phys. Rev. 2, 450 (1913).

[2] Child, Phys. Rev. 32, 498 (1911).

the relation

$$I_p=\frac{2}{9}\left(\frac{2e}{m}\right)^{\frac{1}{2}}\frac{l_p}{r_p\beta^2}E_p^{\frac{3}{2}}\text{ esu,} \tag{3}$$

where β^2 is a dimensionless factor involving a relation between the radii of the plate and cathode. These formal solutions, (2) and (3), hold promise for experimentally determining the charge-mass ratio e/m. Quite apart from the assumption of infinitely extending electrodes, these solutions also assume the absence of gas, zero emission velocity and an infinite cathode temperature signifying an unlimited supply of electrons.

The guard-ring principle allows one practically to ignore the infinity restriction and construct experimental tubes of reasonable dimensions. As for other assumptions, there is a host of evidence indicating the emission velocity to be other than zero and, for the most part, Maxwellian in distribution; but, since the potential difference between anode and cathode can be made large in its effects by comparison, the emission velocity can be dwarfed by the magnitude of the experimental voltage. Although infinite temperature is impossible, high temperatures are feasible; with a high temperature cathode there is a region in plate potential where operation does not deplete the space-charge condition assumed by Eqs. (2) and (3). These remarks are fortified by Fig. 1, where the current-voltage characteristic of a diode is depicted for three conditions.

Consideration of any choice between Eqs. (2)

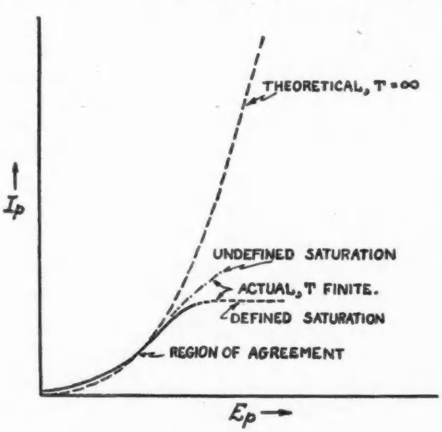


FIG. 1. I_p *vs.* E_p for a diode tube.

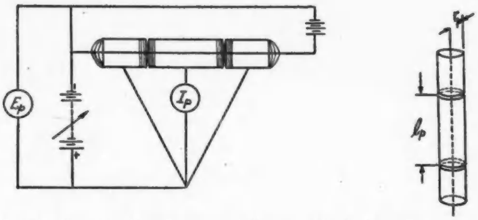


FIG. 2. Conventional guard-ring method, showing some boundary flux.

and (3), with their resulting vacuum tube configurations, makes Langmuir's expression appear the more inviting from many aspects. Fig. 2 indicates the conventional form of guard ring and symmetrically related concentric cylinders for the determination of e/m by Langmuir's solution. In this arrangement the filament is mechanically centered along the axis of the anode, which is seen to consist of three parts. The central portion is the active length l_p. The outer, or guard-ring, portions of the anode are seen to collect current, but this current is not indicated by the plate ammeter. It is noted in Fig. 2 that not all the flux is radial; the fringing flux at the guard rings is effectively thrust to infinite distance in conformity with the derivation of Eq. (3). This experimental method requires special tubes of a costly nature, and often the results are disappointing because of the difficulty in maintaining symmetry and uniform cathode temperature under the active portion of the anode.

Figure 3 illustrates another configuration which has experimental interest and one where the guard-ring principle is reasonably maintained without segmenting the anode. This tube structure consists of symmetrically related concentric cylinders, the inner one being the cathode and the outer one the anode. Both cylinders are rigid, and when properly assembled the arrangement is rugged and dimensionally constant.

It is noted that the cathode of Fig. 3 has fringing flux at its extremities similar to that of the tube in Fig. 2. The blackened portion of the cathode represents a thin coating of highly active material. A heater type of cathode is utilized to maintain the temperature at a value such that the active portion will emit a copious supply of electrons, while the white portion is inactive thermionically. The heater cathode, due

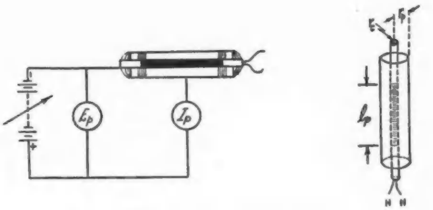


FIG. 3. Emission guard-ring method, showing some boundary flux; $l_p=1.5$ cm, $r_p=0.3175$ cm, $r_c=0.117$ cm.

to its mass and method of heating, also has the advantage of a more uniform temperature along its length. With this structure the cathode emission is abruptly cut off by what might be termed *emission guard rings*, where the change in emission material takes place, well within the plate structure where the flux between the cylinders is assumed substantially radial. The assumption of radial flux may be disturbed by a space-charge spreading at the active tips of the cathode, but this appears to be of a secondary nature.

The emission cut-off effectiveness of this type of cathode can be tested by the saturation current expression of Richardson,[3] expressed as a ratio for different materials. Thus, if the cathode cylinder is composed of nickel thinly coated over its active length with a suitable compound, a ratio between the two materials, where the electron affinity of the nickel is five and the other two, is

$$I_{S_c}/I_{S_{Ni}}=A_cT_c^2\epsilon^{-\phi_c/kT_c}/A_{Ni}T_{Ni}^2\epsilon^{-\phi_{Ni}/kT_{Ni}}.$$

When $T_{Ni}=T_c=1100°\mathrm{K}$ and $k=0.863\times10^{-4}$ v deg^{-1},

$$I_{S_c}/I_{S_{Ni}}=(A_c/A_{Ni})\epsilon^{(\phi_{Ni}-\phi_c)/kT}$$
$$=(A_c/A_{Ni})\epsilon^{31.6}\cong\epsilon^{31.6}, \quad (4)$$

since A_c/A_{Ni} can be considered unity, although it would act to increase the figure $\epsilon^{31.6}$.

Six similar diodes embodying the foregoing ideas and having dimensions approximating the type '56 were obtained,[4] and their plate-current-plate voltage characteristics observed. A composite characteristic of the set is depicted by Fig. 4. These data were subjected to test for e/m with the three-halves power law and Eq. (3). When current is expressed in milliamperes, potential difference in volts and all dimensions in centimeters, Eq. (3) becomes

$$I_p=(2/9)(2e/m)^{\frac{1}{2}}(E_p/300)^{\frac{3}{2}}(10^3/3\times10^9)l_p/r_p\beta^2.$$

Thus, for the dimensions indicated by Fig. 3,

$$e/m=230\ I_p^2/E_p^3\ 10^{17}\ \mathrm{esu\ gm^{-1}}. \quad (5)$$

Applying Eq. (5) to the data of Fig. 4 and plotting values of e/m as a function of the plate voltage, we obtain Fig. 5. The curve tends to level off over a region of plate voltage where the experimental assumptions seem tenable. It is also noted that the value of e/m is high in that region disturbed by the initial velocity of emission and that it is low in the region where the temperature of the cathode is insufficient to produce electrons to maintain a space-charge condition. Too high a plate-current throughout the first region and too low a current in the second region will produce these results as Eq. (5) indicates. It appears, in addition, that whether or not the cathode is saturable is immaterial.

Strictly speaking, values of e/m determined by this method are predicated on the three-halves power law. Thus, only those values of I_p and E_P that strike the proper slope of $\frac{3}{2}$ should be considered. The region of I_p and E_p following the three-halves power law is determined by Fig. 4. For the data presented, it was found that values of E_p conforming to the law are those in the region of 20 v. These are the values of E_p and corresponding I_p that produce good agreement with the accepted value of e/m. Therefore, even

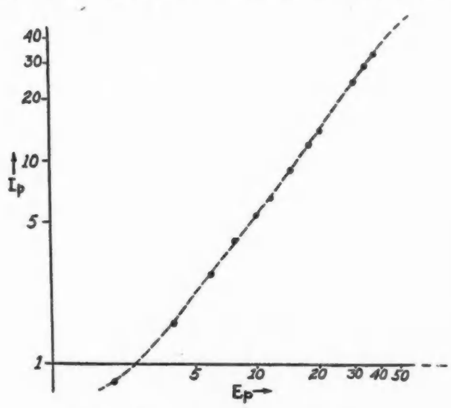


FIG. 4. Log-log composite for six tubes.

[3] Richardson, Phil. Mag. **28**, 633 (1914).
[4] Raytheon Manufacturing Company, Newton, Mass.

though Fig. 5 depicts e/m plotted as a function of E_p, the values of e/m obtained for all E_p's outside the region conforming to the three-halves power law are without physical significance.

The relative accuracy of a measurement of this character is dependent upon how well one knows the tube dimensions and symmetry of alignment of the tube elements. In addition, the measure of I_p and E_p should be made with quality instruments, since in Eq. (5) the plate-current is squared and the voltage cubed. The precision measure of e/m can be predicted from Eq. (5) or prescribed by an equal effects solution having its usual meaning.

This experiment demonstrates that laws are abided by as well as being inadequate. Part of teaching experimental physics is to instruct the student in methods of precision measurement; another part, not by any means to be overlooked, is to present methods of measurement in which the student battles with both mathematical and experimental assumptions, explains the deviation of the measured value from the accepted value, and feels more fortified with knowledge and confidence after the experiment than if the method

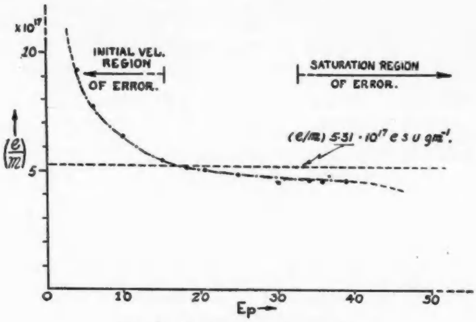


FIG. 5. Curve of e/m *vs.* E_p.

had hinted at measurement as a perfunctory undertaking due to a high relative accuracy. The present experiment should be helpful to those who desire a rugged, inexpensive and reproducible method for charge-mass ratio measurement which, among other things, will give results in keeping with much more complicated and costly apparatus.

The writer wishes to thank Mr. Walter G. Driscoll, Department of Physics, Boston College, for providing and checking the data on the experimental tubes.

Permeability, Induction and Related Concepts in General Physics Textbooks

EDWARD MILTON LITTLE
Department of Physics, University of Montana, Missoula, Montana

THERE is either surprising ignorance or else laxity on the part of recent writers of general physics texts as regards definitions of permeability μ and induction B. For instance, several textbooks define permeability as the ease with which lines of force are produced in a medium. Of some 30 new general physics textbooks examined recently, only about one-fifth of them were blameless in this respect and some of these were silent on many points.

The following treatment of the subject of magnetism of materials is at least consistent. It is not quite the logical scheme that would be used in a graduate course in electrodynamics, but is probably suited to a junior or senior course, using such good texts as Starling or Gilbert, although these texts do not cover all the points we here present. Some, but not all, of this material should be included in the course in general physics.

We define magnetic field strength H at a point as the force per unit north pole placed at the point, the strength of the test pole being negligibly small. This is the usual definition. The lines of *force* are so defined that the number per normal square centimeter equals H. Permeability, in an isotropic homogeneous medium of infinite extent, may be defined by the relation $f = mm'/\mu r^2$ so that μ equals the force between two poles in a vacuum divided by the force when they are in the medium under consideration, if the medium is a fluid. (If the medium is a solid the force increases rather than decreases with μ; thus μ is better defined in terms of Kelvin's definitions of B and H given later; this effect with solids exists because the induced

polarity around a pole is not part of the body being acted upon in the case of a solid medium but is part of the body in the case of a fluid medium.) Strictly, the poles must be point poles and μ must be independent of H. It has been shown by Wilberforce[1] that, for extended magnets, H is not strictly inversely proportional to μ. It is to be noted that, since μ for a ferric chloride solution is greater than 1, the force between poles (and therefore also field strength and lines of force) in this solution is *less* than that in air—the reverse of what some textbooks would have us believe. Permeability is thus a measure of the difficulty, rather than the ease, with which *lines of force* are set up in a medium by a magnet.

Magnetic induction in an infinite isotropic homogeneous medium may be defined as μH. The lines of *flux* or *induction* (not force) are so defined that the number per normal square centimeter equals B.

At this point we call to mind two important boundary theorems about H and B that are proved in many upper class electricity textbooks. At a boundary between two mediums: (1) the components of H parallel to the boundary are equal; (2) the components of B normal to the boundary are equal. These theorems are very useful. For example, Kelvin's definitions of B and H follow directly from them. He defined B and H as the values of H (force per unit pole) in large, thin vacuum slots cut perpendicular and parallel, respectively, to the direction of the field.

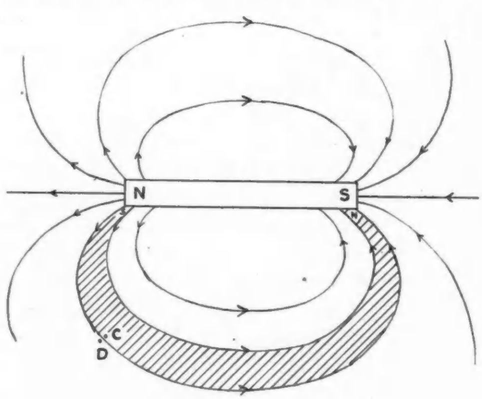


FIG. 1. Bar magnet in air.

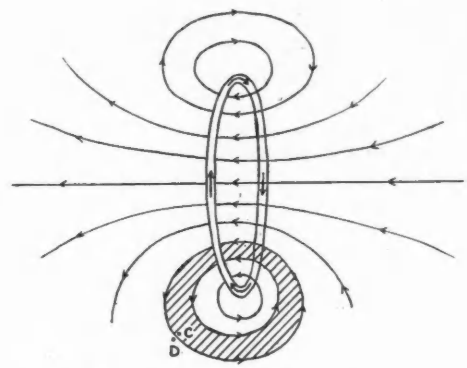


FIG. 2. Loop of wire carrying a current.

Then μ is defined as B/H. These definitions are more elegant and practical than our foregoing tentative ones and are true for solids as well as for fluids, so we will adopt them. (It would be difficult, for instance, to measure the force on a unit N pole when the medium is a solid such as iron; moreover, it would give the wrong value of H.)

As a second application it might not be amiss to remind ourselves why H due to a magnet is less in a paramagnetic medium such as iron, for then we can proceed to see why H due to an electric *current* is *independent* of the permeability of the medium. This latter important fact seems to be little known, but is very necessary when proving that $\int \mathbf{H}\cdot d\mathbf{s}$ around a current is $4\pi i$ regardless of the value of μ. The essentials of these two elegant proofs are due to Jakob Kunz, late professor of theoretical physics at the University of Illinois. To prove that H due to a magnet is less in a paramagnetic medium, take a bar magnet in air (strictly, in a vacuum) and fill one *tube* of force with, say, soft iron, as shaded in Fig. 1. The size of tubes can be arbitrary. But H just inside the tube, at C, equals that in the air just outside, at D. This follows from the foregoing boundary theorem for H, since the boundary is made parallel to the field. But H is less at D than it was before the tube of force was filled with iron because the induced poles at the two ends of the soft iron will be of a polarity opposite to that of the bar magnet, reducing H everywhere in the air. Thus, also, H at C in the iron is less than it was at C in the air previously. By filling the remaining tubes suc-

[1] Wilberforce, Proc. Phys. Soc. London **45**, 82–87 (1933).

cessively with iron, the value of H at C will be reduced considerably; in fact, it will be the original value divided by μ.

To prove that H due to an electric current is independent of the permeability of the medium, apply the same reasoning to a loop of wire carrying a current (Fig. 2). If now one tube of force is filled with iron, there are no induced poles, as the iron has no ends. Thus H at the point D is still the same as before the iron was introduced. Also, since H at points C and D are equal, by the same boundary theorem as before, H at C in the iron is still the same as it was in the air previously. Similarly, and for the same reasons, filling the remainder of the tubes with iron will cause no change. Thus, H (not B) due to an electric current is independent of the permeability.

Three interesting conclusions that may be deduced in part from the foregoing considerations are:

(1) The force between two magnets is proportional to μ^{-1};

(2) The force between a magnet and a current is proportional to μ^0;

(3) The force between two currents is proportional to μ^1.

The first conclusion follows immediately from the Coulomb law, $f=mm'/\mu r^2$. The second was proved in the preceding paragraph—field strength due to a current is really force per unit pole due to a current, and this was shown to be independent of the permeability. Now the second conclusion implies that the force on a current is proportional to B *due to the magnet* rather than to H due to the magnet, as the force is independent of μ. But, by Newton's third law, this force is equal in magnitude (and opposite in direction) to the force on the magnet. Thus, since the force on a magnet is proportional to H, the second conclusion also implies that H due to a current is independent of μ, and hence that B due to a current is directly proportional to μ. Thus if another current (say, in a coil) is in the field of this first current, the force will be proportional to B due to the first coil and this is directly proportional to μ, which is the third conclusion.

As a by-product of this last proof, it may be noted that, since B due to a current is directly proportional to μ, permeability can be considered to be the ease with which lines of *induction* or *flux* (not force) are set up by a *current* (not a magnet).

In dealing with modern electrical machinery, most of our problems are with forces on currents rather than on magnets, and with emf's in wires. These are proportional to B and $\dot{B}$, respectively. Thus B is a much more important concept nowadays than H, at least in electrical engineering, although possibly not in beginning physics. In the past, engineers have often erroneously used the gauss as the unit for B instead of H; in fact, many thought they *were* using H. It is probably for this reason that at Oslo, in 1930, the International Electrotechnical Commission (and then our National Bureau of Standards) named the unit of induction the *gauss*, transferring this term from its former use with the unit of field strength H. For the unit of H, the name *oersted* has been chosen, thus stealing it from the concept *reluctance*. A surprising majority of electrical and general physics textbooks written *since* 1930 have failed to re-define the gauss and oersted in accordance with the new conventions.

January 1, 1940 was the date set for the Giorgi mks system of units to replace the international system,[2] the decisions on choice of the fourth fundamental unit and rationalization being deferred until later. Consequently, it is an appropriate time to discuss the nature of B, H and μ, especially since the tendency now is to make a unit of current primary rather than a unit of magnetic pole, and to define poles in terms of currents (Ampèrian). It must be remembered that, for a magnet surrounded by a medium of permeability μ, Ampèrian currents proportional to the strength of the magnet *and* inversely proportional to μ are the correct substitution, so as to make the resultant field inversely proportional to μ. Of course, if *all* the magnetic material is replaced by Ampèrian currents, not only in the magnet producing the field, but also in the surrounding medium, then μ is assumed to be equal to unity everywhere and H is meaningless. One must be careful to represent a condition in a medium either by Ampèrian currents and $\mu=1$ *or* by magnetic material and $\mu\neq 1$, not, for example, by Ampèrian currents and $\mu\neq 1$. In the mks rationalized system, for a vacuum $\mu=\mu_0=4\pi\times 10^{-7}$ instead of unity.

[2] The war has delayed the execution of this plan; see Am. J. Phys. **8**, 78 (1940).

Physics for Students Preparing for Medicine

John R. Loofbourow
Research Laboratories of Institutum Divi Thomae, Cincinnati, Ohio

The teaching of physics to those who are entering the medical profession has received considerable attention in recent years, especially with regard to what can be done to improve the physician's knowledge of physical principles.[1] That many physicians would welcome a more thorough knowledge of physics was evidenced by our experience with a series of lectures on "Radiant Energy in Medical Science" conducted through cooperation of the University of Cincinnati and the Cincinnati Academy of Medicine several years ago. The lectures were attended regularly by nearly a hundred physicians, many of whom spent considerable extra time in inquiry about physical matters.

In fifteen years' research and teaching experience with physicians and medical students, I have found a distressing lack of knowledge of even fundamental physical concepts on the part of many medical men. Our experience with the physicians' lecture series and with our own research workers indicates that this is not due entirely to lack of interest. What, then, is the trouble? Most of those in the medical profession of whom I have inquired have insisted that the fault lies principally in the instruction offered. Probably their contention is worthy of serious consideration.

Those who have already investigated the problem have suggested various remedies. A recent committee report[2] recommends a requirement of two years of physics, instead of one, for entry to medical colleges. It is suggested that the first year be devoted to the usual beginning course, and the second to a special course for those entering medicine.

Despite favorable results obtained with a course of the latter kind offered, a few years ago, to a group of thoroughly prepared premedical students at the University of Dayton, we are convinced that a second course in physics holds little hope of helping the situation in the average instance (even though it may be offered profitably to selected groups) because it avoids two fundamental problems: (1) No amount of training in physics or biophysics will make up for lack of a working knowledge of algebra, trigonometry, analytic geometry and the calculus; and (2) a second course in physics designed to interest biological and premedical students cannot substitute for a lack of interest developed in a poor beginning course.

It is possible, after several years of experimentation, for us to make certain comments regarding the problem of mathematical background. Ours is an institution that, in its teaching activities, purposes to give a broad training for, and an intensive experience in, research to a small group of postgraduate students. In the majority of instances, these students are expected (after three or more years) to enter subsidiary research centers operated under the direction of the parent institution.

Almost all the earlier students who came to us were biologists, biochemists, or chemists. Their previous training presented, in many cases, the usual lack of mathematical background and understanding of physical principles. We decided to face this fact frankly and to remedy it by whatever procedure (no matter how drastic) seemed necessary. Accordingly, training in mathematics through the calculus was made compulsory for everyone. Such training is now a prerequisite for entrance, and is waived only in special cases in which the deficiency can be made up without too great delay.

To those who argued that the calculus is "too difficult" for "nonmathematical-minded" biologists, we answered that, if such logical disciplines as mathematics were above the mental capacity of any candidate, he was not the kind of person we wanted. Actually, once the first fear complex was overcome, our most worried biologists made satisfactory progress in mathematics and enjoyed the work. A few continued,

[1] "Physics in relation to medicine," Am. J. Phys. (Am. Phys. Teacher) **2**, 48, 101 (1934); E. L. Harrington, J. Assoc. Am. Med. Coll. **7**, 362 (1932), Am. J. Phys. (Am. Phys. Teacher) **2**, 176 (1934).

[2] "Report of the committee on the teaching of physics for premedical students," Am. J. Phys. (Am. Phys. Teacher) **5**, 267 (1937).

of their own volition, with such additional subjects as differential equations and elementary vector analysis. This was accomplished with students who were much older than premedical students and proportionally more opposed to innovations in training.

We are convinced, from this experience, that it is not unreasonable to require an adequate mathematical background of everyone studying physics—whether he is an engineer, a premedical student, or a biologist. We believe that more can be accomplished by insisting on such mathematical prerequisites than by teaching second courses in physics to students who think that a cosine is a fraternity emblem and a square root an unusual plant specimen.

Our experience indicates that the second problem is equally deserving of attention. Too often, the first course in physics is taught by a physicist whose narrow outlook precludes his being truly interested in biological or biophysical problems. Such a man cannot be expected to stimulate the interest of biologists, biochemists and medical men, anymore than one who sees nothing important in bridge stresses can be expected to hold the attention of engineers.

It is not essential for the physicist who teaches premedical students to oversimplify his subject in order to bring to them a live enthusiasm for his field, a genuine confidence in the fact that the knowledge he is helping them to acquire will be useful to them, and a willingness and ability to discuss problems which arise from their special interests and experiences. Underestimating the intelligence of the college man (as is the present vogue in some "survey courses" and in certain physics textbooks for "arts" students) only pushes the level of college down to that of high school and leaves us with poorer, instead of better, trained men.

It *is* necessary, however, that the instructor in physics for premedical students have a broad understanding of the applications of physics in medical and biological fields as well as in engineering. He should be able to convince his listeners that the principles of physics are universal in their applicability. He should show them that it is this very universality which makes it essential to state so many physical concepts in abstract terms. He should not, as many now do, teach engineering applications rather than physical principles.

There is much precedent for physicists to interest themselves in biological and physiological problems. Maxwell was no less a physicist because he toyed with color tops, nor was Thomas Young any less distinguished in physical circles because he happened to be a physician. Let it be noted that these men saw keenly the world about them, and, whether they were creating crystal-clear patterns with intricate mathematical equations, or looking straight to the heart of illusive secrets in involved physical experiments, they never permitted their vision to be clouded by the illusion that they were God's elect, working in His chosen field, and not to be contaminated by contact with anyone from another sphere. It seems to me that there is much we can learn from them in dealing with the present problem. I daresay that Maxwell and Young could have made physics intensely interesting to the average premedical sophomore, and that they could have accomplished this without our present-day muddling attempts to improve classic rigor by pulling rabbits out of hats and telling the students that they really shouldn't mind where the rabbits come from.

In brief, then, the solution to the problem of improving the physics training of premedical students seems to us to lie in two directions: first, the insistence on adequate mathematical preparation as a prerequisite, or corequisite, for entry into the first physics course (a requirement which becomes less onerous with the increasing tendency to lengthen the period of premedical training from two to three or four years); and second, the selection of instructors for the first course who have a broad interest in biological and medical, as well as engineering, problems, and who are capable of discussing medical applications of physics intelligently.

The history of an exact science does not deviate markedly from its structure as developed logically.—MAX PLANCK.

NOTES AND DISCUSSION

Two Problems

1. Suppose that three identical gears, A, D and E, are attached to the shaft of a constant speed motor (Fig. 1), and that D drives the gear B at twice the angular speed of the motor shaft, while E drives C at half the shaft's angular speed. If, now, a card be touched successively to the teeth of gears A, B and C in the manner of a Savart wheel, how will the resulting pitches be related? A moment's consideration suggests that the pitches will be, respectively, n, $2n$ and $\frac{1}{2}n$—an obvious but incorrect conclusion.

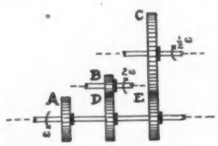


FIG. 1. Problem 1.

2. A block of paraffin or of ice floats nine-tenths submerged in a vessel of water. If, now, sufficient oil of specific gravity 0.85 be poured on top of the water so as to cover the block, will the block descend still farther into the water because of the increased pressure above it, will it stay with the same fraction submerged or will it rise into the oil? I find that a class of students is likely to be divided upon the correct answer, and that the actual performance of the experiment elicits surprise and interest. As the oil is poured into the vessel, the block rises until a large fraction of its volume is above the water level. The experiment speaks eloquently for itself and it may, of course, be made the basis of numerical problems.

RICHARD M. SUTTON

Haverford College,
Haverford, Pennsylvania.

Concerning the Poundal, In Reply to Salviati

THAT was an interesting discussion reported by H. M. Dadourian in a recent issue,[1] and I wish I had been in the group that carried it on. I should have agreed with Salviati in his defining equations, and in his definition of force in terms of mass and acceleration. But I should have objected to his condemnation of the poundal, and his bringing together "the poundal and the slug" as if they both arose from the same objectionable equation.

Since I now have had the advantage of reading Professor Dadourian's comments on the initial version of the present note, and since he has been good enough to answer a personal letter in which I confessed my perplexity, I am not so confused and resentful as I was after reading—and re-reading—the original discussion. But still I think that Salviati should be answered. He makes out an unfair case against the poundal, and by implication an unfounded charge of perversity or stupidity against those who use it.

On reading the original paper[1] I thought, and I am sure that others would think, that Salviati objected to the poundal as being something which it is not. For he and Simplicio repeatedly refer to ". . . the poundal and the slug. . . ." as used to make k unity when the equation $F=kma$ is written as an algebraic expression of Newton's second law. However, Dadourian explains that this does not mean that both the poundal and the slug are to be used at once. Obviously, if m is in *slugs*, a is in *feet per second*^{2} and k is unity, F is not in poundals. Accordingly, Salviati must be saying that the poundal arises as a unit of force if we write $F=kma$, express m in *pounds*, a in *feet per second*^{2} and choose such a unit for F as makes k unity. That seems to be the only way to connect the poundal with k, as Salviati certainly does. But the poundal comes in when k is left out. It seems remarkable to me that Dadourian should insist, as I do also, on writing $F=ma$ as a definition of force, and yet should object to the poundal as a unit of force. For certainly F is in poundals if m is in *pounds* and a in *feet per second*^{2}. The real objection must be, it seems, to the use of the pound as a unit of mass. For with that unit, and $F=ma$ as the equation, the poundal is, so to speak, inevitable. Yet Dadourian will have none of the slug. Neither will he write $m=w/g$. He then has no English unit of mass at all.

Dadourian's general contention seems to be that we should use an absolute system of units, but, in order to conform to the usage of practical men, we should disguise the absolute unit in the result and express forces in pounds. This is one more variation on the common practice of placating the engineer by not trying to teach him anything. Well, so far we have no dictators in this country. We can still say, *De gustibus non est disputandum*. We must allow Professor Dadourian to have his own way in his own work. However, I think his discussion is unfair to the absolute system of units and to the poundal. There is mass, and there is a unit of mass properly called the pound. We all teach a system of grams, centimeters, dynes and ergs. To these correspond exactly the pound, foot, poundal and foot poundal. Two parallel systems are no more difficult to learn than one—perhaps less difficult. Why should the student be led to believe that in an English system one must form different units in a different manner? If $F=mv^2/r$ gives *dynes* in one system, it gives *poundals* in the other; K.E. $=\frac{1}{2}mv^2$ gives *ergs* and *foot poundals;* moment of inertia is in *gram centimeters*^{2} in one system and *pound feet*^{2} in the other.

It might seriously be claimed that the poundal made things too easy. If this simple system makes physics too difficult for students, let them elect other subjects.

W. W. SLEATOR

University of Michigan,
Ann Arbor, Michigan.

[1] "On the meaning of a constant in a physical law," Am. J. Phys. (Am. Phys. Teacher) 7, 241–243 (1939).

Physics for the Masses

THE majority of people apparently know little about the usefulness of physics. They need to become aware of the fact that even a slight knowledge of physical principles can help them in their everyday work and can save them many dollars in the selection of the most effective, efficient and durable machines and appliances.

Statistics gathered by the United States Bureau of Education give evidence of this lack of understanding on the part of the masses. As Table I shows, physics was

TABLE I. *Ratios of percentages in 1934 and 1928.*[1]

SUBJECT	SCHOOLS OFFERING	STUDENTS TAKING
Physics	47.3/49.8 =97%	5.23/ 6.85 =76%
Biology	63.2/52.2 =121	12.1 /13.6 =89
Chemistry	37.3/32.5 =115	6.34/ 7.05 =90
General Science	71.0/66.8 =116	15.1 /17.5 =86

[1] Computed from data given by C. A. Jessen and L. B. Herlihy, Sch. Life **22**, 314, 320 (1937). For a brief digest of this article, see Am. J. Phys. (Am. Phys. Teacher) **6**, 53 (1938).

offered by a smaller percentage of the high schools in 1934 than in 1928, whereas all the other sciences showed an increase in the percentage of schools offering them. Although, during the six-year period, the percentage of students enrolled in the entire group of sciences decreased in the nation as a whole, physics suffered the largest decrease. There were two notable exceptions to this general trend: North Carolina showed a large increase in the percentages both of schools giving physics and of students taking it; Maine showed some increase in both percentages and stood above the national average. A further indication of the attitude of educational administrators is seen in the fact that the new president of a southern college for teachers has eliminated the department of physics; he states that science teachers should be trained in the universities where the scientific equipment of engineering colleges is available.

Some possible reasons for this whole situation may be listed as follow:

1. The need for economy in establishing new schools during the depression led many administrators to omit from the curriculum subjects that are expensive to house, equip and maintain.

2. Poorly trained teachers do a worse job of teaching physics than those in other subjects. A poorly trained teacher cannot point out or explain the practical applications of physics; hence, his students naturally suppose that it has no applications in their daily life. He must give much time to the maintenance of the laboratory and equipment, and should keep in touch with the many new developments in his field; yet, in addition to this, he must share in all the extra-classroom duties required of the teachers in other fields. Many school boards seem unaware of these demands and will accept physics teachers with less specific training in their field than they require of teachers of other subjects.

3. Some states no longer require the high school mathematics generally considered necessary for beginning the study of physics. Many high school students believe that they will not need algebra, geometry or physics unless they go into some branch of engineering, and parents often encourage them in this belief. If, later in their high school courses, they become interested in some phase of science or engineering, they may feel that it is too late to go back and get the necessary mathematics.

4. In many colleges and universities, students entering with a unit in physics are placed in the same course with beginners in the science. Although this does not necessarily mean that college professors regard high school physics as useless, it is apt to be so interpreted by school administrators and students.

5. Physicists do not advertise their accomplishments. Whenever a chemist makes an outstanding contribution to society he is called a great chemist but a physicist making a similar contribution is likely to be hailed as a great scientist. Approximately one-third of the contents of the average high school textbook in chemistry is physics, but to the students it is all "chemistry." Even the catalogs of apparatus manufacturers often list beam balances, polariscopes, spectroscopes, thermometers, calorimeters, etc., as "chemical apparatus." It is no wonder that students are predisposed to think of physics as dry and difficult, dealing with such "impractical" matters as relativity, electron spins and cosmic rays, and of chemistry and biology as the really active and worth-while sciences.

In sponsoring Professor Harrison's *Atoms in Action*, the American Institute of Physics is to be commended for an excellent attempt to help change the attitude of the public toward physics and to make people realize how interesting it is to understand why common machines operate as they do. Some of the chapters in *Atoms in Action* are so clearly and simply written that even young school students can understand and be thrilled by these stories of how some great industry has been built upon the early experiments of certain physicists.

We need many more such books, especially some written in even simpler language. Children in elementary school are quite interested in scientific matters. For instance, pupils in the fourth, fifth and sixth grades who were allowed to work with and make individual measurements on levers, the buoyancy of liquids, etc., showed a surprisingly keen ability for recognizing the correct generalizations involved, often doing so more accurately than many college freshmen. Other investigations have shown that many fundamental physical concepts can be learned as easily in the various high school grades as in college. To have available interesting accounts, appropriate for the various school grades, of the ways in which physicists discovered and developed these concepts and principles obviously would be advantageous.

As another specific example of how we might help to correct the situation physics is facing in the schools, we should show athletic coaches that it is much easier to teach athletes to get the most out of their efforts if they understand the physical principles involved in their stunts. Witness the world records broken in the last few years after the coaches began to study the physical principles involved in pole vaulting, high jumping, hammer throwing, etc. We should show slow motion pictures of these events,

and discuss the physical applications; for example, a short piece of the film "Happy Landing" serves to show how the skating of Sonja Henie illustrates the transformation of energy of translation into that of rotation. Many other phases of athletics can be used to show the practical character of physics. Indeed, with a knowledge of physics, particularly if it is acquired early in life, much of our work and play can be done more easily, safely and efficiently; for example, the driving of an automobile is an extended experiment in physics.

Of course, we also should never allow ourselves to forget that the chief function of any course is to help the student learn how to think for himself, and that physics is perhaps the easiest of all subjects with which to accomplish this purpose.

C. R. Fountain

George Peabody College for Teachers,
Nashville, Tennessee

Abstract from a Report to the Executive Committee of the American Association of Physics Teachers

During a leave of absence for the year 1938–1939, the writer made visits to some 60 colleges. On authority of the Executive Committee of the American Association of Physics Teachers he made the effort to be of some service to the association during these visits. As a result, the attitude of many physicists toward the association was learned. For the most part, there was evident a growing satisfaction in association activities and accomplishments. The healthy state of the organization itself testifies to this. Unfortunately, there was also noted a lack of interest on the part of too large a portion of the physics teachers in the larger research universities. An attempt to analyze this situation appears to lead to two primary causes.

First, the association seems to lack any real sponsorship in these particular institutions. The "higher ups" are members of the association but apparently do not prevail upon their colleagues to take even this interest. A little support and boosting by the proper men in these institutions by way of a membership campaign should bring about a greater appreciation for the association and a larger membership at the same time.

Second, the most common criticism seems to be in regard to the papers and the discussions at the meetings of the association. Too many papers give only an expression of opinion or a description of teaching systems or methods insufficiently tried. In a scientific organization, the opinion is that the papers should be supported by scientific experiment and presented and discussed on a more scientific basis. The following suggestions are made for possible improvement in this respect: (1) that the secretary be given editorial aid in making out the programs so that a mechanism for rejection or revision of submitted papers may be available; (2) that abstracts, of say 100 words, be printed in the program.

Many physicists seem to feel that the association can do them no good. If they can be made to consider the good which they themselves can do for physics and for science in general, through membership, the future welfare of the American Association of Physics Teachers will be doubly assured.

Francis G. Slack

Vanderbilt University,
Nashville, Tennessee.

Introduction of the Concepts of Work and Energy

When one considers that the concepts of work and energy are fundamental in physics it seems very inappropriate that they are first introduced by a purely arbitrary definition. The difficulty is increased by the fact that when the definition of work is applied to a simple case—holding a weight in the hand—in which it is very obvious that a person gets tired, it is not at all obvious that work is being done; the observation that the hand really moves up and down is far less direct than the observation that the activity is fatiguing. It would seem desirable to have the definition of work and the principle of conservation of energy develop naturally from principles of physics that have previously been mastered. This result can be obtained by a slight rearrangement of the topics usually presented in the first course, together with a shift in emphasis.

The topic of simple machines is studied by analyzing each machine by means of the principles of equilibrium. Some machines require the use of the principle of the equilibrium of a particle only, others, the principle of moments only; still others require a combination of these principles. One seeks a single unifying point of view for this collection of force multipliers, or machines, and finds it in the velocity ratio. Then, for each machine separately, it is easily shown that the product of force and distance moved in the direction of the force is transmitted without loss. Hence that product has some standing, in mechanics at least, and deserves a name.

Since the product of force and distance moved in the direction of the force is significant in connection with the constant velocities met in the study of machines, it is natural to inquire whether that product also has any fundamental significance in connection with accelerated motions. The mathematical steps are given in all textbooks; but the meaning is that the concept of kinetic energy has already been postulated, so that the mathematics is used to deduce the formula. In the development indicated here we are merely curious to find out whether any result will emerge from our attempt to extend a concept from the realm of statics to that of motion with acceleration. Like Newton, we are framing no hypotheses. When it turns out that the product of force and distance moved yields a formula, $\frac{1}{2}mv^2$, which depends only upon the end conditions, we begin to suspect that we are on the verge of a great discovery. We note that the use of a large force to give an object a final speed v is automatically compensated by the fact that the final speed is reached by traveling a shorter distance; the product of force and distance is independent of those details. We may even convince ourselves that the acceleration need not be constant; the final speed may be

attained in several stages, during each of which the acceleration has a different value. Thus a moving object has associated with it something equivalent to the force-distance product of a machine. An experiment is suggested: to see if a moving object can really act on a machine and produce the same result as does a force moving through a distance. A satisfactory experiment would be difficult to perform; unless the moving object were slowed down very gradually it would perform an amount of work on the machine substantially less than $\frac{1}{2}mv^2$. However, even an unsatisfactory experiment would demonstrate that a moving object does possess some ability to re-create a force-distance product.

To clinch the understanding of the new concept, energy of a moving object, one applies it to motion in a circle with constant speed. Here there is an accelerating force, but no change in speed; consequently there is no change in energy. The student already knows that the accelerating force is perpendicular to the direction of motion under these circumstances. Hence the student will be led to conclude that a force so directed is not a working force. This will help to indicate why the original idea had to require that the force be in the direction of motion.

An interesting by-product of this approach is a better understanding of the differential pulley. Analysis of this machine by means of the principles of equilibrium indicates why it is supplied with a chain instead of a rope. The hand exerts a small force on the chain at one point; yet when one determines the force in the chain on the other side of the pulley one finds it rather large—half the weight which is to be lifted. Since, in the first study of simple machines, one assumes that there is no friction, we should have a paradox if there were no cogs to make up the difference in force.

Through its tie-up with the theory of simple machines this approach to the energy concept in mechanics stresses the necessity that friction be absent. This circumstance provides a natural motivation for the next extension of the energy concept; the conditions under which the energy concept appears to lose its validity are just the conditions that result in the production of heat.

Robert S. Shaw

College of the City of New York,
New York, New York.

Radioactive Standards

A series of radioactive standards, prepared under the direction of the Committee on Standards of Radioactivity of the National Research Council, will be deposited at the National Bureau of Standards to be issued as working standards to investigators who desire them. The standards now under preparation are:

(1) *Radium standards.*—(*a*) 100-ml solutions sealed in 200-ml Pyrex flasks containing 10^{-9} and 10^{-11} gm of radium to be used as emanation standards either directly or by subdilution; (*b*) 5-ml solutions sealed in Pyrex ampoules containing various masses of radium to be used as γ-ray standards.

(2) *Thorium standards.*—Sealed ampoules containing sublimed $ThCl_4$ for use in preparing standard thorium solutions.

(3) *Standard rock samples.*—100-gm samples of ground rock from 12 different localities, analyzed for radium and thorium content and intended for use in extraction of radon and thoron from rock samples.

Accurate knowledge of the radioactive content of the materials of the earth's crust is of primary importance in many phases of physical science. Reliable radioactive standards are also essential in studies of radium and thorium poisoning and in biologic and medical investigations using the technic of radioactive indicators, or internal artificial radioactivity therapy. For the latter purposes calibrated standard sources of β-particles will be made available. It is hoped that these various standards will provide all workers in these fields with a common basis for comparison of measurements and also improve the accuracy of all the measurements.

The committee will be glad to cooperate as far as possible in aiding investigators to use these standards to the best advantage and will welcome specific inquiries regarding their use. Any suggestions regarding other desirable radioactive standards, not at present available, should be submitted promptly. In particular, it will facilitate the work if laboratories and individuals that can make use of these standards advise the Committee of their probable requirements. Address the Chairman, Professor Robley D. Evans, Massachusetts Institute of Technology, Cambridge, Massachusetts.

Mathematical Tables

A project for the computation of tables of fundamental importance in mathematics and the physical sciences, sponsored by Dr. Lyman J. Briggs, Director of the National Bureau of Standards, Washington, D. C., is being conducted by the Federal Works Agency, Works Projects Administration for the City of New York. The project has been in operation since January 1, 1938 under the technical supervision of Dr. Arnold N. Lowan. A table of the first ten powers of the integers from 1 to 1000 and a comprehensive table of exponential functions have already been published. Comprehensive tables of circular and hyperbolic functions, trigonometric and exponential integrals and certain physical tables have been completed and are now in process of reproduction. Tables of probability functions and Bessel functions for complex arguments are now in progress. Doctors A. N. Lowan and G. Blanch have published, in the February issue of the *Journal of the Optical Society of America*, a paper entitled "Tables of Planck's radiation and photon functions." Requests for copies of the National Bureau of Standards tables should be sent to Doctor Briggs.

RECENT PUBLICATIONS AND TEACHING AIDS

General College Physics

Physics. Erich Hausmann, Thomas Potts Professor of Physics and Dean of Graduate Study, and Edgar P. Slack, Associate Professor of Physics, Polytechnic Institute of Brooklyn. Ed. 2. 762 p., 471 fig., 14×22 cm. *Van Nostrand*, $4. The general plan and good features of the 1935 edition have been retained in the present, revised edition of this textbook for students of science and engineering. A change has been made in the sequence of the chapters on electricity and magnetism, the material on vector operations has been merged into a single chapter, the treatment of force has been rearranged, and the material on recent advances and technologic applications has been modernized. New problems have been added to bring the total to 800, and many other improvements of a minor character are evident.

Survey Courses

A Survey in Physical Science. John Stuart Allen and others, Colgate University. 482 p., 209 fig., 15×22 cm. *Harper*, $3. A course was organized at Colgate University in 1930 "to orient freshmen in the fields of astronomy, chemistry, geology and physics" and to give them "a definite conception of the physical world, some appreciation of the scientific method and the part it has had in the intellectual life of the race, as well as the contributions of the physical sciences to the solution of some contemporary problems." The present textbook, an outgrowth of this course, is intended to be a selective, integrated and unified treatment, rather than a series of condensed versions of the several sciences represented, with no attempt being made to give the student a fair representation of what may be expected by taking further work in any or all of the departments concerned. However, astronomy and geology certainly have not been subordinated in the book; in comparison with the explicit references to these two sciences, the similar references to physics and physicists are almost negligible in number. Many of the concepts of physics are introduced in connection with astronomical topics, leaving only two of the 15 chapters—less than one fifth of the text—to be prepared by a physicist, Clement L. Henshaw. Chemistry does not fare much better. The treatment as a whole tends to be descriptive and informative, rather than analytic and critical, and it does not adequately reflect and utilize the physical and chemical principles and methods that are most characteristic of physical science and most responsible for its great power. All this is unfortunate, for the book in other major respects appears to be scientifically sound and to have numerous excellent features. Each chapter of the book is provided with a set of questions and a list of books recommended for supplementary reading.

Intermediate and Advanced Physics

Cosmic Rays. Robert A. Millikan, Chairman of the Executive Council of the California Institute of Technology. 142 p., 42 photographs and diagrams, 5 tables, 14×21 cm. *Macmillan*, $2.50. This monograph contains revisions of three lectures given by the author at the University of Virginia and at Trinity College, Dublin, on (1) the discovery, history and general significance of cosmic rays, (2) superpower particles, and (3) the earth's magnetic field and cosmic-ray energies. Although concerned primarily with the work carried out by the group at the Norman Bridge Laboratory, the lecturer takes account of the most significant contributions of other workers, thus giving a condensed, but exceedingly interesting, general picture of present findings in this field.

A Textbook of Heat. Part I. H. S. Allen, Professor of Natural Philosophy, University of St. Andrews, and R. S. Maxwell. 552 p., 41 tables, 200 fig., 14×22 cm. *Macmillan*, $3.25. The present part of this two-volume British work is intermediate in grade, and mainly descriptive and experimental in character. The method of approach is historical but modern developments are not neglected. The mathematical treatment is relatively simple, the little calculus notation that is employed being adequately explained. Worked examples, problems with answers, and questions accompany each chapter. Reserved for the second volume is the material of a more theoretical and advanced nature; for example, the laws of thermodynamics and the more exact treatments of such subjects as the transfer of heat and radiation, statistical methods and the quantum theory.

Problems in Mechanics. G. B. Karelitz, Professor of Mechanical Engineering, Columbia University, J. Ormondroyd, Professor of Engineering Mechanics, University of Michigan, and J. M. Garrelts, Associate Professor of Civil Engineering, Columbia University. 280 p., many diagrams, 15×23 cm. *Macmillan*, $2.50. Many of the 782 practical problems in statics, kinematics and kinetics contained in this volume came from the collection of the late I. V. Mestchersky and his assistants, among whom were engineers of prominence in various fields. The problems are classified according to subject and are of a wide range of difficulty. English units are employed throughout. The problems are supplied with answers and approximately 75 of them, selected as typical, are furnished with solutions. All are preceded by a 50-page review outline of the theorems essential for their solutions.

Popular Books

Atoms in Action. George Russell Harrison, Professor of Physics, Massachusetts Institute of Technology. 380 p., 19 photographs, 22×15 cm. *Morrow*, $3.50. With

physicists in this country more conscious today than ever before of the desirability of bringing their profession to public attention in every legitimate way, the appearance of a popular book so ably conceived and generally acceptable that it can be unreservedly recommended to all classes of readers is a timely event. However, as is well known, the timeliness and the appeal of Professor Harrison's fine book are not matters of accident. Undertaken at the instance of the American Institute of Physics because of the obvious need for popular books in physics comparable in quality and appeal to popularizations existing in certain other fields, the book shows what can be contributed when an able scientist who has wide interests attacks the task of presenting his subject to the general public with the same determination and respect for the difficulties involved as he would have in dealing with a purely scientific problem. Physicists should take advantage of every opportunity to bring this book to the attention of all classes of readers, and to insist that it be made available in every school, college and public library.

The World of Science. F. SHERWOOD TAYLOR. 1080 p., 533 fig., 48 plates, 15×23 cm. *Reynal and Hitchcock*, $3.75. Covering the fields of physics, chemistry, geology, astronomy and biology, this survey presents a well-balanced and authoritative picture of the present state of scientific knowledge. The sections on physics, which comprise more than half the book, discuss nonmathematically and in terms understandable to the layman most of the phenomena and theories usually presented in a general physics textbook. While much space is devoted to the engineering applications of physics and little to the more sensational modern developments, the point of view is always that of the scientist rather than that of the engineer. Wherever possible, the author, a chemist, explains phenomena in terms of the behavior and structure of molecules; he employs many diagrams of molecular models as pictorial aids for his discussion of the molecular structure of matter and theories of chemical action.—H. N. O.

Activities of Association Chapters

CHICAGO

THE Chicago Association of Physics Teachers met on November 11, 1939, Dr. R. J. Stephenson presiding. After a luncheon at the Lawson T.M.C.A., a session was devoted to a consideration of the means of testing the results of teaching physics, the invited speakers being Professor Richardson, Director of Examinations, University of Chicago, and Dr. Max Englehard, Director of Examinations, Chicago City Junior Colleges.

R. E. Harris, Lake Forest College, was elected president of the chapter for 1940, and Professor Walter E. Peterson was reelected secretary. Professor Harris represents the chapter on the executive committee of the Association.

COLORADO-WYOMING

The Colorado-Wyoming chapter held its annual meeting in conjunction with the Colorado-Wyoming Academy of Science on October 20, 1939, at the Colorado State College of Agricultural and Mechanical Arts. Several papers were presented at a joint meeting with the physics section of the Academy.

Officers elected for 1940 are J. C. Stearns, University of Denver, *President*, and M. C. Hylan, University of Colorado, *Secretary-Treasurer*. W. B. Pietenpol, University of Colorado, represents the chapter on the executive committee of the Association.

OREGON

The Oregon chapter met on November 18, 1939, at Pacific University. The following program was presented at morning and afternoon sessions:

Preparation of Specimens for Growing Crystals and for Polarization of Light. F. JONES, *Pacific University*.
Mobility Spectrum of the Atmospheric Ions. E. A. YUNKER, *Oregon State College*.
Building Physics Equipment. J. R. WATSON, *Pacific University*.
Instruction in Physics in Austria. E. BETH, *Reed College*.
Atomic Electron Velocities. M. A. STARR, *University of Oregon*.

At two sessions held on February 17, 1940, at Willamette College, the program was as follows:

Photographs of Experimental Set-Ups. J. C. GARMAN, *Oregon State College*.
The Columbus Meeting of the Association. A. A. KNOWLTON, *Reed College*.
Research for Civil Aeronautics Authority. M. O'DAY, *Reed College*.
Construction of an Electron Multiplier Tube. J. J. BRADY, *Oregon State College*.
Teaching the Aviation Theory of Flight to Civilian Pilot Trainees. W. V. NORRIS, *University of Oregon*.

Officers of the chapter are: Marcus O'Day, Reed College, *President;* Wm. R. Varner, Oregon State College, *Secretary-Treasurer;* A. E. Caswell, University of Oregon, *Additional Member of Executive Committee*. A. A. Knowlton represents the chapter on the executive committee of the Association.

WESTERN PENNSYLVANIA AND ENVIRONS

The Association of Physics Teachers of Western Pennsylvania and Environs held its sixteenth meeting on November 4, 1939, at the University of Pittsburgh. A display of demonstration apparatus was a feature of the meeting. The program was as follows:

Why Should Students of Pharmacy Study Physics? C. T. VAN METER, *School of Pharmacy, University of Pittsburgh*.
A Statistical Study of High School Physics in Lawrence County. J. A. SWINDLER, *Westminster College*.
The Use of Public Demonstration Lectures to Popularize Physics. O. BLACKWOOD, *University of Pittsburgh*.
Energy Transformations and Some Graphed Relationships. H. W. HARMON, *Grove City College*.
A Protective Device for A.C. Clocks. W. H. MICHENER, *Carnegie Institute of Technology*.
The Rubber Band as Demonstration Equipment. M. H. TRYTTEN, *Johnstown Center, University of Pittsburgh*.
Symposium: The Teaching of Physics in Colleges for Women. E. E. STICKLEY, *Pennsylvania College for Women*, W. J. STALEY, *Margaret Morrison College, C.I.T.* and K. F. OERLEIN, *California State Teachers College*.

Bernard L. Brinker, St. Vincent College, is secretary of the chapter.

Summer Courses and Meetings

University of Washington

The American Association of Physics Teachers will meet on June 26–30 at the University of Washington, Seattle, in connection with the meeting of the Pacific Division, American Association for the Advancement of Science. Professors A. A. Knowlton, Reed College, and F. A. Osborn, University of Washington, are in charge of the program and local committees, respectively. The Meany Hotel will be hotel headquarters for the meeting.

University of Iowa

The fifth summer colloquium for college physicists will occur on June 13 to 15. Some of the new features of the program are: an evening devoted to exhibits of new laboratory experiments; a day's consideration of the first course in physics for nontechnical students; and applied subjects in the oil and radio industries and in music, the discussions being led by specialists in these fields.

Cornell University

A course in *Theoretical and experimental electronics* will be offered by Professor Lloyd P. Smith during the 1940 summer session. Designed to fit the needs of students possessing varying degrees of preparation and experience in this field, the course will consist of lectures and laboratory work on such topics as the nature of a gas, modern high vacuum technic, electron optics, thermionic and secondary emission, the photoelectric effect, collisions of electrons with atoms and their relation to phenomena in electrical discharges. The usefulness of these phenomena in the development of the cathode-ray tube, electron microscope, kinescope, iconoscope, etc., will be pointed out. The rather extensive laboratory equipment and facilities available will make it possible for students to acquire experience in a wide variety of topics, and allow more advanced students to carry on experimental work of a semi-research character.

The interactions of electrons with atoms, especially as exhibited in various types of collision processes, will be considered from a somewhat more advanced point of view in a separate course on *Physical phenomena from the point of view of the wave theory of matter*. The inadequacy of classical mechanics for describing atomic collision phenomena in electric discharges, conductivity, secondary emission, etc., will be pointed out. The necessary fundamental concepts as furnished by the quantum theory will be presented and applied to the correct description of the foregoing phenomena without undue emphasis on the mathematical details.

Appointment Service

REPRESENTATIVES of departments or of institutions having vacancies are urged to write to the Editor, Columbia University, for additional information concerning the physicists whose announcements appear here or in previous issues. *The existence of a vacancy will not be divulged to anyone without the permission of the institution concerned.*

Positions Wanted

27. Ph.D., physics, Northwestern '35; A.B., engineering, Harvard. Age 42, married, 3 children. Experience: 1 yr. lt., artillery; 12 yrs business and sales; 5 yrs college teaching. Interested in undergraduate teaching, including astronomy.

29. Ph.D., Northwestern; M.S., Pittsburgh; A.B., Muskingum. Age 34, married, 1 child. Has had 13 yrs teaching experience in two universities. Interested in teaching and research.

30. Ph.D., Univ. of Chicago. Many years experience as head of department of physics in prominent college. Author of books on physics and history of science. Large work on history of physics in preparation. Interested in college or university teaching.

31. Ph.D., Columbia. Years of experience as head of departments of physics in colleges and universities. Author of new type of laboratory manual. Designer of many new types of simplified apparatus. Research in radio, acoustics and methods of teaching physics.

33. M.S., experimental physics, coupled with thorough background of courses in professional education. Has taught physics and mathematics for 3 yrs in large high school. Desires position as instructor in high school physics in a university or college experimental or training school.

34. Ph.D., M.S., Penn State. Age 38, married. 13 yrs teaching experience in colleges and universities; 3 yrs head of department in small college; industrial research experience. Interested in teaching, research and administrative work in a small college.

35. Ph.D., Purdue; M.A., British Columbia. Age 27, married. Experience: 5 yrs university teaching; 2 yrs secondary school teaching; 5 yrs research in analysis of liquids by x-rays. Interested in teaching and research.

36. Ph.D., Pennsylvania '37; M.S., A.B., West Virginia. Age 30, married. Has taught 4 yrs in small liberal arts college of good standing. Interested in a position of greater responsibility and opportunity.

37. Ph.D., engineering physics, mathematics and physical chemistry, Illinois. A.B. in education. Age 37, married. Experience: teachers college, junior college and high school teaching; 1 yr editorial work. Interested in research and physics teaching. Especially qualified for survey courses.

Departments having vacancies or industrial concerns needing the services of a physicist are invited to publish announcements of their wants; there is no charge for this service.

Any member of the American Association of Physics Teachers may register for this Appointment Service and have a "Position Wanted" announcement published without charge.

Vacancy

Lecturer in physics, Judson College, Rangoon, Burma. The appointee must have at least a master's degree, be an active member of a Protestant church, be willing to serve five years, and must sail not later than June. The stipend will at least meet actual living expenses; residence, and passage to and from Burma are provided. Judson College is a constituent college of the University of Rangoon, and is located on the beautiful new campus of the University Estate on Kokine Lakes. Instruction is in English. Apply to Dr. R. L. Howard, American Baptist Foreign Mission Society, 152 Madison Ave., New York, N. Y.

DIGEST OF PERIODICAL LITERATURE

Marconi and Radio Communication

Guglielmo Marconi and the development of radio communication. A. Fleming; *J. Roy. Soc. Arts* **86**, 42–63, Nov., 1937. Marconi's work on practical wireless telegraphy undoubtedly laid the foundation of a great industry. Although he was not the first to transmit alphabetic signals by electromagnetic waves, he was the first to provide a simple, portable and easily managed apparatus for intercommunication over long distances on land and sea. This, resulting in the saving of hundreds of lives, earned him the gratitude of the entire world.

The starting point of all advance in radio communication was Maxwell's great memoir of 1865, in which he introduced the idea of electric displacement and proved that electric and magnetic field changes were propagated as waves with the speed of light. In 1883 Fitzgerald suggested that the oscillatory discharge of a Leyden jar might generate Maxwell waves; but it was not until Hertz, in 1887, formed a condenser circuit with the metal plates at the ends of a metal rod and a spark gap at the center that the existence of electromagnetic waves was demonstrated by reflection and refraction experiments. In 1879 Hughes, the inventor of the microphone, discovered that a metal and a carbon rod in loose contact, or a tube loosely filled with metal particles, was sensitive to an electric spark. Calzecchi-Onesti in 1884, Branley in 1891 and Lodge found that such a contact, called by Lodge a *coherer*, had a large resistance until a small e.m.f. was applied. In 1894 Lodge used a coherer in a Royal Institution lecture to demonstrate some of Hertz's discoveries. Requested to repeat his lecture, Lodge added a Kelvin dead-beat signaling mirror galvanometer in series with the coherer and a tapper, similar to that of an electric bell, to tap the coherer back to a nonconducting state after signal reception. Using a Hertz oscillator, he transmitted dot and dash signals recorded by small and large galvanometer deflections; this was the first electric-wave telegraph.

Marconi, 20 years old at that time, made a Hertz oscillator of much greater radiating power by using a pair of spark balls, one connected by a long vertical wire to a large metal plate, the other to a plate in the earth. The coherer was improved, a telegraphic relay to operate a Morse printer added, and the entire receiver was enclosed in a metal case. Marconi applied for a British patent and, in 1897, transmitted excellent signals nearly 9 mi over water and 4 mi over land. At about the same time Lodge applied for a patent on a similar transmitter and tuned receiver—the first syntonic system—and Admiral Sir Henry Jackson seems independently to have discovered the great advantage of earthing one oscillator ball while connecting a long vertical wire to the other. Thus Marconi, while responsible for many improvements that increased the range of electric waves, was not the sole inventor of wireless telegraphy.

In 1899 Marconi attracted public interest by sending messages across the English channel. At this stage he introduced a transformer called a *jigger* to change the large current variations at the aerial base to large potential variations on the coherer. The aerial used by Marconi at this time radiated strongly damped oscillations, making tuning impossible. By inserting Leyden jars and a variable inductance between the aerial and the earth, and by tuning circuits in receiver and transmitter to one frequency, Marconi produced his first syntonic system in 1901 and applied for a patent. The courts held that Lodge was the initiator of syntonic wireless but also upheld Marconi's method for putting it into practice.

Returning from America in 1899, Marconi was determined to attempt transmission over the Atlantic, and the author [Fleming] was engaged as engineering adviser. A plant, using a 25-hp engine and similar alternating dynamo with 2000–20,000-v transformers and special condensers, which consisted of glass plates coated with tinfoil immersed in stoneware pots filled with linseed oil, was erected at Poldhu on the Cornwall coast. In December, 1901, Marconi in Newfoundland, using kites and balloons to elevate his aerial, heard in a telephone placed in series with a coherer faint triple sounds (the Morse code for *S*), the prearranged signal from Poldhu. However, the result excited some doubt and criticism because of the difficulty of its explanation as a diffraction effect. At this time Heaviside and Kennelly suggested that a conduction layer in the upper atmosphere affords a reflecting and refracting region for electric waves, and thus began the theoretical and experimental work in this field which has continued to the present time. In 1902, while crossing the Atlantic, Marconi noted that signals sent out from Poldhu remained almost unchanged in strength both day and night for 500 mi but that day signals disappeared at 700 mi, while night reception was good to over 1500 mi and decipherable to over 2000 mi.

For projecting electric waves in a given direction, Marconi first followed Hertz and, as early as 1896 or 1897, used short waves and metal parabolic mirrors to achieve transmission over a distance of 2 mi. In 1905 he found that a bent antenna with only a short vertical portion radiated most strongly in a direction opposite that to which the free end pointed and also best received waves from the same direction. This discovery in directive wireless telegraphy, made without mathematical prediction, illustrates Marconi's remarkable power of intuitive invention which was aided by an unfailing perseverance and enormous power for continuous work. Investigation of direction location of shore stations by ships at sea was continued by several workers, some in the Marconi Company. The formation of this company in 1897 showed

Marconi's power to convince others of the commercial value of his work.

From 1901 to 1908, when public wireless service both ways across the Atlantic was first established, Marconi exhibited his great courage, fertility of invention and power to work even 16 hours a day to overcome the many difficulties presented by transoceanic telegraphy. A station was set up at Glace Bay, Breton Island and, later, one at Clifden, Ireland, which was replaced, because of the Irish "trouble," by one at Snowden near Carnarvon. Wooden lattice towers were erected, the engine and dynamo power increased to 150 hp and the wave-length changed to about 8000 m. New apparatus included large air condensers with metal plates a foot apart, direct-current dynamos joined in series to charge a high-voltage storage battery, and a rotation spark discharger which suppressed the arc discharge but allowed the oscillatory condenser discharge to take place. The Snowden station used high-frequency Alexanderson alternators. Finally, all old methods of electric-wave production were superseded by the use of thermionic valves.

After the discovery by amateurs of the effectiveness of short waves from low power transmitters because of reflection from the ionosphere, Marconi, assisted by C. S. Franklin, threw himself into short wave work with his characteristic energy. Skeleton parabolic mirrors made of vertical wires were first used to form a beam. After success with low power transmitters a 12-kw station was built at Poldhu. Experiments on the Marconi yacht, Elettra, showed day and night reception at 1250 and 2230 mi, respectively, with strong signal strength. Franklin next constructed long aerial wires cut up into sections by coils or condensers. By placing a number of such aerials parallel to each other, arranging another set behind them at the proper distance for reflection and using powerful valve oscillators, it was possible to project strong beams of wave-lengths 15 to 90 m upward at a slight angle into the ionosphere. In 1924, 32-m waves using less than 12 kw were received well in Buenos Aires and Australia. Short wave Imperial Beam stations were erected for the British government for day and night communication with all parts of the world, the receiving and transmitting stations always being some distance apart. In his last years Marconi, assisted by G. A. Mathieu, worked on ultra-short wave transmission, and on his recommendation the Vatican authorities adopted a 60-cm wave for communication between Vatican City and Castel Gandolfo.

Marconi's predominant interest was in the practical applications of scientific knowledge. He complied in a high degree with the definition of an engineer given in the Charter of the Institution of Civil Engineers, as "one who utilizes and controls the energies of Nature for the assistance and benefit of mankind."—H. N. O.

Apparatus and Demonstrations

An experiment in electrostatics. W. C. Hill; *Sch. Sci. Rev.* **21**, 885–886 (1939). An electroscope is enclosed in a wire cage of about ½-in. mesh, on an insulating stand. The cage and the electroscope knob, respectively, are connected to the knobs of two other electroscopes with grounded cases. When the cage is charged, each electroscope indicates the potential difference between its leaf and case, and the enclosed electroscope shows no divergence. The knob of this electroscope is now grounded by touching it with a wire inserted through a mesh of the cage, and the resulting deflections are noted. A variety of other groundings may be tried. The experiment illustrates clearly the fact that an electroscope indicates potential difference and not charge.—J. D. E.

Demonstrating long-wave fluorescence. H. D. Murray; *Sch. Sci. Rev.* **21**, 875–876 (1939). Fluorescence may be induced in certain dyes of the rhodamine class by light of the visible spectrum (up to the yellow); the light emitted is red. Test tubes are filled with 0.25-percent solutions of rose bengale and of rhodamine 6G and 0.5-percent solutions of phloxin, brilliant kiton red B, pyronine and rhodamine G. The tubes are backed with white cardboard and illuminated in a darkened room with a 0.5-w incandescent lamp provided with a housing and filter. A blue-green filter may be prepared from an unexposed, fixed and washed photographic plate by soaking it for 10 min in a 1-percent filtered solution of disulphine green V.S., rinsing for 1 or 2 sec in water and standing it vertically on blotting paper to dry. A 0.2-percent solution of toluidine blue will produce a blue filter in the same way. Under white light all six solutions have a magenta hue. The rose bengale solution does not fluoresce and, when illuminated by light transmitted by the blue-green filter, changes to blue. With the other five solutions the red fluorescence is superimposed on the blue, and the hue varies from violet to dark red. The red fluorescence may be cut out by viewing the solutions through the same kind of filter as that with which they are illuminated. The demonstration may also be carried out with strips of natural white silk dyed in each of the solutions, slightly acidified with acetic acid.—J. D. E.

Check List of Periodical Literature

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